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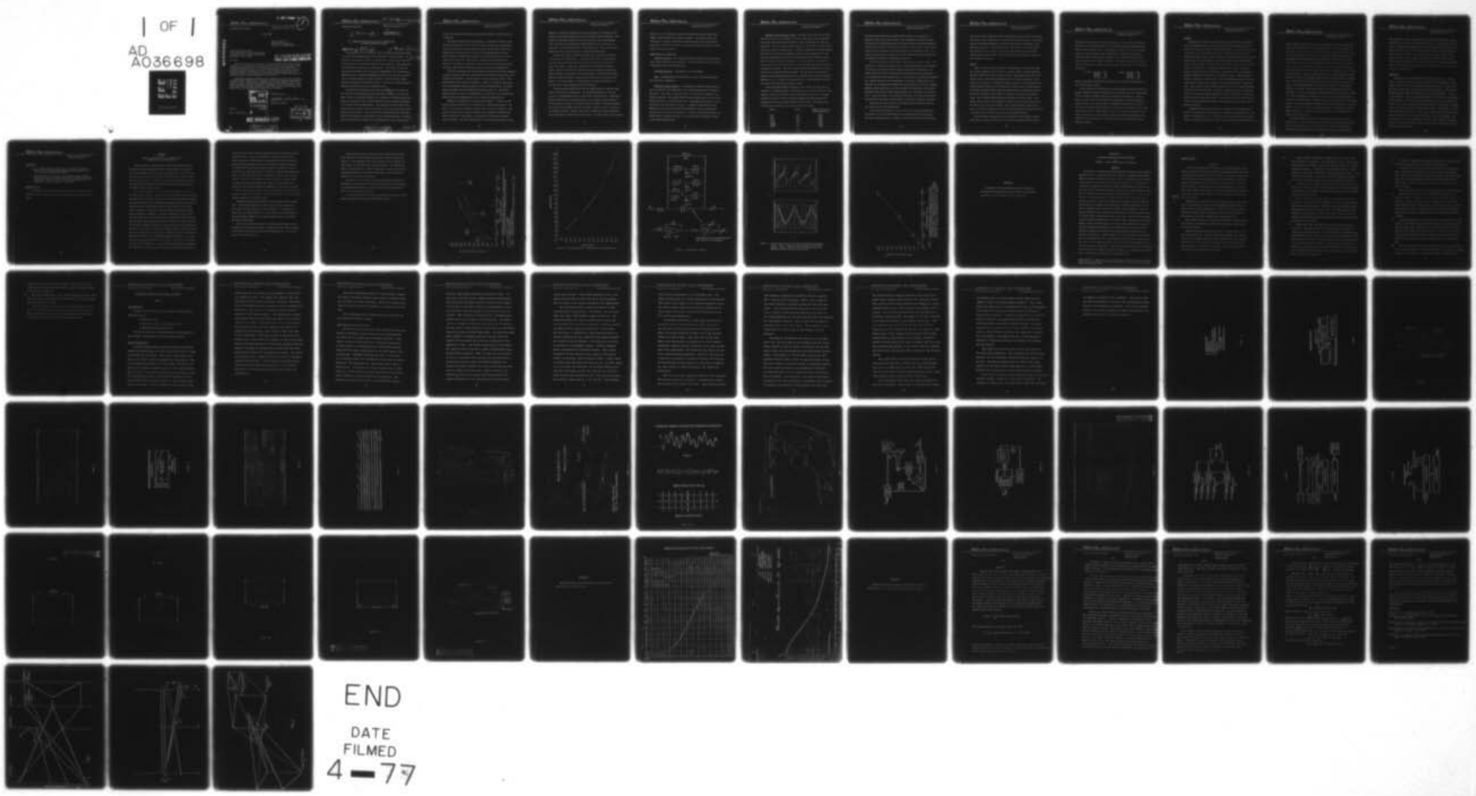

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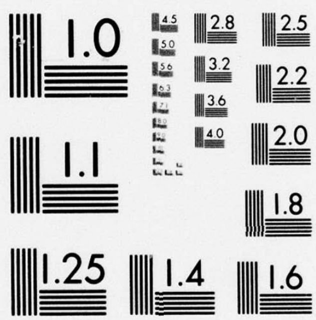
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Willow Run Laboratories

Geophysics Laboratory

INSTITUTE OF SCIENCE AND TECHNOLOGY
THE UNIVERSITY OF MICHIGAN

7 June 1966

ADA036698

Report 07275-4-L
Final Letter Report for
Contract N140(70024)78176B new

Signal Processing Branch
U. S. Navy Underwater Sound Laboratory
Fort Trumbull, New London, Connecticut
Attention: Eugene Green

Dear Sir:

The final report of this contract is concerned primarily with linearity, distortion, and dynamic range of the process of recording and harmonic analysis with photographic film. The description of such an investigation is included. An initial attempt was made at predistortion of signals to compensate for inherent non-linearities of the film recording system after the report was written. Therefore, the description of the introduction of predistortion and its results are included as an addendum.

Previously, detailed drawings of our commutating and recording apparatus were prepared and delivered, as recording and film transport were then current problems at USL. Although not a specified area of this contract, the Meyer-Eppler technique has been concurrently investigated at this laboratory. Since USL is concerned with this technique, a derivation which we have prepared for other work at our laboratories is included as an Appendix.

Sincerely yours,

Philip L. Jackson

Philip L. Jackson

PLJ:cmr

Atch: Final Report

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Willow Run Laboratories (15) N140(70024)78176B

Geophysics Laboratory

INSTITUTE OF SCIENCE AND TECHNOLOGY
THE UNIVERSITY OF MICHIGAN

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Report 07275-4-L
Final Letter Report

(6) LINEARITY AND DYNAMIC RANGE OF A PHOTOGRAPHIC FILM DATA PROCESSING SYSTEM.

INTRODUCTION (11) 7 Jun 66 (10) Philip L. Jackson

Photographic film is non-linear. Yet, for coherent optical processing it is used for recording signals and processed as if it were linear. In (12) 76p. the system to be discussed film is recorded from a cathode-ray tube, where the signal input is represented through Z-axis modulation. This modulation is non-linear with respect to a voltage input. Our task is to find the linearity and dynamic range of signals on photographic film recorded from a cathode-ray tube. Since the photographic film is to be processed linearly, that is, through taking the Fourier transform, the film ideally should linearly correspond to the recorded signal. One desires a linear transformation but finds two non-linear transformations.

To study the non-linearity, the relationship between the output and the input of the recording and processing system is found. For this purpose a series of reference functions was recorded on variable-density film. They were recorded in such a way that different levels could be diffracted in an optical system simultaneously. The intensity of first order diffraction from each reference level was measured, as well as the one higher order generated by distortion. By this means the relationship between the input signal to the output was determined for each recorded frequency. A previous treatment which did not include the recording process can be found in Ref. 1.

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In this way the optical recording and processing system was thus treated as a black box.

The system consisted of input amplifiers, commutation circuits, Z-axis modulation of the bias of the cathode-ray tube, imaging lens, photographic film on a film drive, and the developing process of the photographic film. Additionally, the measurement was taken in a diffractive optical system which includes the light source (laser in this case) and the means of collimating and imaging the light source to obtain Fraunhofer diffraction patterns. The black box, therefore, consists of all these elements between the signal input and the diffracted energy caused by the developed film.

We first investigated the non-linearities of the system and then attempted to minimize them by choosing a suitable bias level with the anticipation of introducing predistortion. Numerous defects in our system were found. Only photographic film was used for recording. However, the response characteristics of photographic film are similar to those of photochromics, and thermoplastic recording is also fundamentally nonlinear (Ref. 2). The Hurter-Driffield curve is similar in photochromics, so that many of the results and problems found with photographic film are found with photochromics.

Briefly, the investigation was conducted as follows. A number of sinusoidal reference functions were recorded from a laboratory oscillator. The level of the reference functions extended over a range of 46 decibels. The amplitude levels of the reference functions were recorded at slightly different frequencies. One channel was employed for each of seven separate reference levels. The film containing the seven reference functions was then

placed in a diffractive optical system whose aperture was apodized to normalize for frequency differences and the modulation transfer function. The resulting diffraction pattern was examined visually, and on photographic film. The number and intensity of higher harmonics were examined as an indication of the distortion of the recording process. The energy in each diffracted order was measured with a scanning microphotometer.

Each set of a total of eleven different sets of reference functions was recorded on a different day. The proper bias level was determined by recording the maximum amplitude of the reference functions at many different bias levels. These were then placed in the diffractive optical system. The bias level which resulted in the least amount of second harmonic diffraction was chosen as the most suitable. The bias levels of the diffracted light intensity, including higher harmonics, were measured and plotted. From these plots we calculated the required predistortion of the input for a linear output of the optical system.

The investigation showed that with 2 mm width channels, a dynamic range between 40 and 46 db is achievable. The harmonic distortion is very low, in fact is not detectable except at the maximum amplitude level. Significant harmonic distortion was not found, because, it is thought, of the nature of the distortion caused by the recording system and medium. The large displacements tend to be smoothly reduced or extended, so that the sine wave tends to be smoothly distorted. However, the amount of diffracted energy corresponding to amplitude of signal input is not linear. The bias level on our recorder

turned out to be difficult to control, with wide variations in bias both within a day's recording and between recordings. The departure from non-linearity was, however, much less than the deviation in bias from channel to channel. The lack of a stable, repeatable bias level was the most significant defect in our system.

DESCRIPTION OF THE EQUIPMENT

Reference Function. The sinusoidal reference functions were generated with a Krohn-Hite Model 44 A Oscillator. The amplitudes were read on either a Type 564 or Type 547 Tectronix Scope.

Recording Apparatus. See Appendix 1 for description.

Film. Recordak Dacomatic SO-266 film was used. The data sheets for this film are in Appendix 2.

Diffractive Optical System. A conventional Fraunhofer diffractive system was employed. The light source was a Spectra-Physics Model 115 Helium Neon Laser. The light was focussed with an 8 mm microscope objective on a 20 micron pinhole. The pinhole formed the point light source for the system. Bausch & Lomb 12" f 2.8 lenses were used. The diffraction pattern was scanned with an Intectron Model VS-12A-M-3. An Eldorado Model 201 Universal Photometer with a Dumont Type 6292 Photomultiplier tube was employed for measurement of intensity of diffraction. A 22.7 mm microscope objective was used to focus the light energy on a 1 mm x 12 micron slit located in front of the photomultiplier tube.

Recording and Measurement of Film. The first task is to set and determine the bias level of recording. To achieve this the intensity adjustment of the Type 531A Tectronix Oscilloscope is first calibrated for intensity modulation. For this purpose a photomultiplier is attached to a Model 23-050 Jarrel-Ash scanning microphotometer. With the oscilloscope intensity adjustment set at its maximum the reading is taken on the microphotometer. The intensity adjustment is then set to a predetermined level which was determined by experiment in the following manner. The reference signal at its maximum level, in this case 1.4 volts, was repeatedly recorded, each time at a different bias level. The films were then used for diffraction to observe the amount of second harmonic generation. The bias level was chosen for which the second harmonic generation was a minimum; hence the total harmonic distortion was at a miminum for this bias level. Third and higher harmonics were found only with extremes of bias levels.

Seven sinusoidal reference functions over a 46 db range were then recorded on 2 mm width channels. All functions were recorded on the same film with the channels side by side, with each reference function at a slightly different frequency so that all could be diffracted simultaneously while spatially separated for energy and visual measurements. The voltage and corresponding frequencies are listed in the columns below.

Voltage	hertz	Spatial Frequency in cycles/millimeter
1.4	8	7.60
0.7	7.5	7.12
0.28	7.0	6.65
0.1	6.5	6.17
0.028	6	5.70
0.014	5.5	5.22
0.007	5	4.75

The lower signal levels were assigned successively lower frequencies to diffract closer to the central image. This arrangement was aimed at being conservative in the determination of the dynamic range, since the background intensity (or noise) of the light is greater when closer to the central image. Seven reference functions were recorded each day on 11 different days. No changes or alterations were made to the system during this time, except that two different measurement oscilloscopes were used.

Each reference film was then put in the diffractive optical system. All channels were diffracted simultaneously. Polaroid photographs of the diffraction pattern were examined for the number and location of harmonics. The range between the lowest unambiguously detectable harmonic and the highest was considered to be the dynamic range of the recording and diffractive apparatus. Higher harmonics, due to distortion, were noted. Additionally, each harmonic was measured with the photometer and the square root of the intensity plotted against input level. Due to the noise and limitations of the photomultiplier setup only the first four harmonics were detectable under diffraction. Second harmonics, if of sufficient intensity, were also measured with this device for the amount of distortion in the maximum amplitude recording.

The films were also scanned on the Jarrel-Ash microphotometer for the bias levels of each recorded function.

As Fraunhofer diffraction is measured with an energy detecting device the outputs of the scanning photometer were proportional to the square of the linear quantity desired. Therefore, linearity was checked by taking the

square root of the diffractive output and plotting this against the corresponding voltage input. These plots were made for the 11 sets of film. The average and the standard distribution were found for the energy measurements on the diffracted harmonics. The bias levels were also plotted. These plots first were made for all 11 records, and also for 6 which fell inside reasonable control limits on bias levels. The response curve for design of a predistortion network was drawn up.

RESULTS

Figure 1 shows the plot of amplitude of diffraction versus signal input for 11 films, Figure 2 for the best six. Maxima, minima, standard deviation and bias variation are shown on the two plots. The dynamic range varies from 34 db to 46 db. Every record which did not have widely varying bias levels showed at least 40 db. We defined the dynamic range as the range between the widest amplitudes which can be recorded with a given maximum of distortion to the smallest amplitude which will show unambiguously on a diffraction pattern. Of the 11 recordings, 8 were 40 db, 1 was 46 db, and 2 were 34 db dynamic range. The two which showed 34 db were defective in the bias level. They either varied widely between different channels or were too far toward one or the other extremes on most channels. When we define dynamic range in this manner we conclude that for a 2 mm channel width recording on Recordak 266 film a practical range of 40 db was achieved in this optical system.

The distortion was indicated by the amplitudes of the second harmonics. Except for the films in which the bias level was extremely shifted a higher

harmonic was found only for the maximum voltage. Only a second harmonic was detectable. The second harmonic was, if prominent enough, measured with the aid of a photomultiplier tube. When below the range of the energy-measuring device the second harmonic in the photograph was compared with the first harmonic of the smaller voltage amplitudes for an estimation of the percentage of second harmonic higher distortion. The distortion ranged between 2% and 7% for the maximum voltage when all 11 films were measured, 2% and 5% for the best 6.

11 films:	average:	4.1%	6 films:	average:	3.1%
	maximum:	7%		maximum:	5%
	minimum:	2%		minimum:	2%
	st. dev:	1.8%		st. dev:	1.1%

Again, no harmonic distortion was detectable for recordings of voltages $\frac{1}{2}$ or less of the maximum voltage.

As the film must be linear in the light amplitude transmission characteristics to prevent harmonic distortion, one would expect that this would indeed be the case when no higher harmonics are found under diffraction. However, when the square root of the intensity of diffraction is plotted against the voltage level of the reference input a logarithmic shaped curve was found. The lack of detectable higher harmonics and the lack of linearity in the energy plots appears to be a contradiction. However, the type of distortion of the signal is such that, a small amount changes the linearity considerably. The distortion is in the form of a smooth compression or expansion of the sinusoidal wave shape.

COMMENTS

Possibly the distortion was spread over many harmonics or continuously over non-integral harmonics. At any rate this lack of correlation between observable harmonic generation and lack of linearity was unexpected (see, for example, Ref. 1). This type of distortion is different from the type of harmonic distortion found in tape recording in which odd harmonics are formed (principally the third harmonic). The maximum displacement may be changed only slightly with tape recording while a significant amount of harmonic distortion is introduced. For diffractive purposes of spectral analysis or Fourier analysis this fact is fortunate. At the most often used amplitudes harmonic generation is limited to -40 decibels at worst. Thus unambiguous spectral readings can be found over a range of approximately 40 db. The magnitude of the readings can be referred to the slope found with a particular film. Values within a known standard deviation can then be found through the calibration curve of the film. As a known reference function can usually be recorded on one of the signal channels, the entire processing can thereby be processed with an internal reference. What is said about the lack of distortion in the diffraction plane also can be applied to one or two-dimensional spatial filtering.

A particular optical system has been treated here. Its particular defects serve to emphasize the problems to be found in any optical system. For purposes of future design of a similar system, the most important contribution is the determination of the weaknesses of a previously constructed system.

The two major weaknesses of this system are in the shift of recording bias level from channel to channel and from time to time, and the inherent non-linearity. The former is caused by idiosynchrasies individual to this system while the latter is to be found in any similar optical system whether photographic film, photochromic or thermoplastic. The cause of the bias shift found here has not been definitely determined. Several possibilities exist. These are the variation or displacement in the slit which is placed on the front of the cathode-ray tube, drift in the multiplier circuit, drift in the multiplier scope, the eyeball difficulties in determining the proper bias when reading the monitoring scope (under the present system the adjustments call for extremely fine discriminations on the part of the operator). There is also the probability of intermittent dc drift on the Krohn-Hite reference oscillator. These are typical of the difficulties found in any such system. The general problem of non-linearity, which also will be found in a similar optical and recording system, can be minimized through the introduction of predistortion. For this system, and indeed for most conceivable systems, a type of exponential amplification of the input signal is required. Figure 3 is a curve of the estimated gain for such an exponential amplifier. Such an amplifier is, of course, achievable but has not at this time been constructed for this system.

The photomultiplier and its associated photometer were tested in two separate ways: first by introducing Kodak neutral-density filters into the system and observing the change in output due to the light attenuation of these filters, and second by a method which is probably most suitable for

this application. This method consisted of putting a high quality, Ronchi transmission grating into the diffractive system.-- in other words a square wave. The output of the photometer was plotted against the intensities of the odd harmonic numbers. Such an indication of linearity most closely resembles the manner of the tests of the linearity of this optical system. In each case linearity to within a few percent was found with no trends above or below linearity. Thus within our margin of error the manufacturer's claim of 0.5% linearity appears valid for the device used for measuring the intensity of diffraction.

CONCLUSIONS

Many details can be substantially improved in this system. For instance, control of bias level and the introduction of predistortion. This optical system can be used to perform spectral analysis over a range of 40 db with an average of a maximum of 3.1% harmonic distortion. This harmonic distortion occurs only at the extreme range of input amplitudes. In view of the nonlinear steps of the recording process the results show surprisingly little distortion. The type of distortion minimizes measurement difficulty because only a small amount of observable harmonics are generated. One might term this type of distortion as compressibly smooth. It manifests itself in changing the linearity of the output without substantially introducing higher harmonic distortion -- an unexpected discovery of this investigation. The enumeration of the present deficiencies of this system should be beneficial in the design and use of future systems for other data media such as thermoplastics or photochromics.

REFERENCES

1. E. N. Leith, "Photographic Film as an Element of a Coherent Optical System," Photographic Science and Engineering, Vol. 6, No. 2, pp. 75-80, March-April, 1962.

2. Radar Laboratory, Study of the Applicability of Thermoplastic Recording Techniques to Coherent Optical Processing. University of Michigan, Institute of Science and Technology, Willow Run Laboratories, Report 4563-104-T, July, 1965.

ACKNOWLEDGEMENT

The author would like to acknowledge the excellent experimental work of Ronald H. DeVee, who recorded all of the films with a fractions camera system.

ADDENDUM

Addition of Predistortion to Compensate for Nonlinearity in Film Recording

Tests of the film produced by the multichannel seismic recorder have indicated that amplitude distortion occurs between the input to the camera multiplexer and the image produced on film. In view of the nonlinearities involved in CRT phosphor illumination and film exposure this is not surprising. In order to reduce the distortion in the camera intentional predistortion of the opposite kind was introduced between the input and the recording system.

The curve in Figure 3 shows the desired input-output response of the predistortion circuit. A device having an amplitude response closely approximating the desired curve was constructed using a Tectronix Model O operational amplifier unit. The desired amplitude response curve was obtained by using a four segment piecewise linear approximation to the curve in Figure 3. The tectronix Model O amplifier contains two independent operational amplifiers. The first amplifier is used to scale the input signal to a convenient operating voltage for producing the desired response, and to invert the signal so that after a second inversion by the other amplifier the output of the circuit has the same polarity as the input. The scaling is based on multiplying both the ordinate and the absissa of Figure 3 by a factor of 25. Amplifier A then has a gain of 25. The gain of amplifier B is controlled by the input voltage so as to produce the desired predistortion characteristic. The manner in which this is done is shown in Figure 4. Four separate feedback paths are provided for amplifier B. In the region of operation where the output voltage is

less than 15 v the four feedback circuits operate in parallel to produce a gain of 1.08 for segment 1 of the curve. When the output voltage reaches about 15.4 v (15 volt bias on the diode plus 0.4 v drop in the diode) diode F_4 conducts and removes the feedback furnished by branch 4. The removal of this branch raises the gain of amplifier B to 1.43. In like manner, diode F_3 conducts at about 24 v and increases the gain to 1.85. Finally, diode F_2 conducts at about 28 v and increases the gain to 2.5. The output of amplifier B is shown in Figure 5 together with the input sawtooth which produced this output. The comparison of an input sine wave with the output from amplifier B is also shown in Figure 5. The peaked-up positive portion of the output signal is apparent. The output of amplifier B is followed by an attenuator to restore the overall signal amplitude to its original level.

Predistortion was first inserted on one side only of the recording bias. The resulting diffractive output values of one recording for four input reference signals are shown in Figure 6. A maximum of 1.2 volts reference input amplitude was used in place of 1.4 volts because the predistorted amplitude of the higher voltage would have saturated our present electronics.

The bias drift between channels was reduced considerably from that described in the body of the report. Second harmonic distortion produced at the maximum (1.2 volts) was barely discernable by eye. It was estimated to be between $\frac{1}{2}$ and 1%.

Approximately symmetric predistortion was added to the opposite input polarity, and the resulting diffractive amplitudes plotted in Figure 7. Here significant bias level variation between channels was again found, the variation being approximately 18%. Harmonic distortion is approximately 5%. The bias level again is seen to be the most significant problem in our recording apparatus. Circuit redesign is anticipated to alleviate this problem.

It is thus seen that photographic film (and hence photochromic, recording can be made close to linear with little harmonic distortion) as indicated by this hurried, initial attempt with an approximative piecewise circuit for predistortion.

I want to thank Rowland McLaughlin and Harold Welch for the prompt design and construction of the predistortion network.

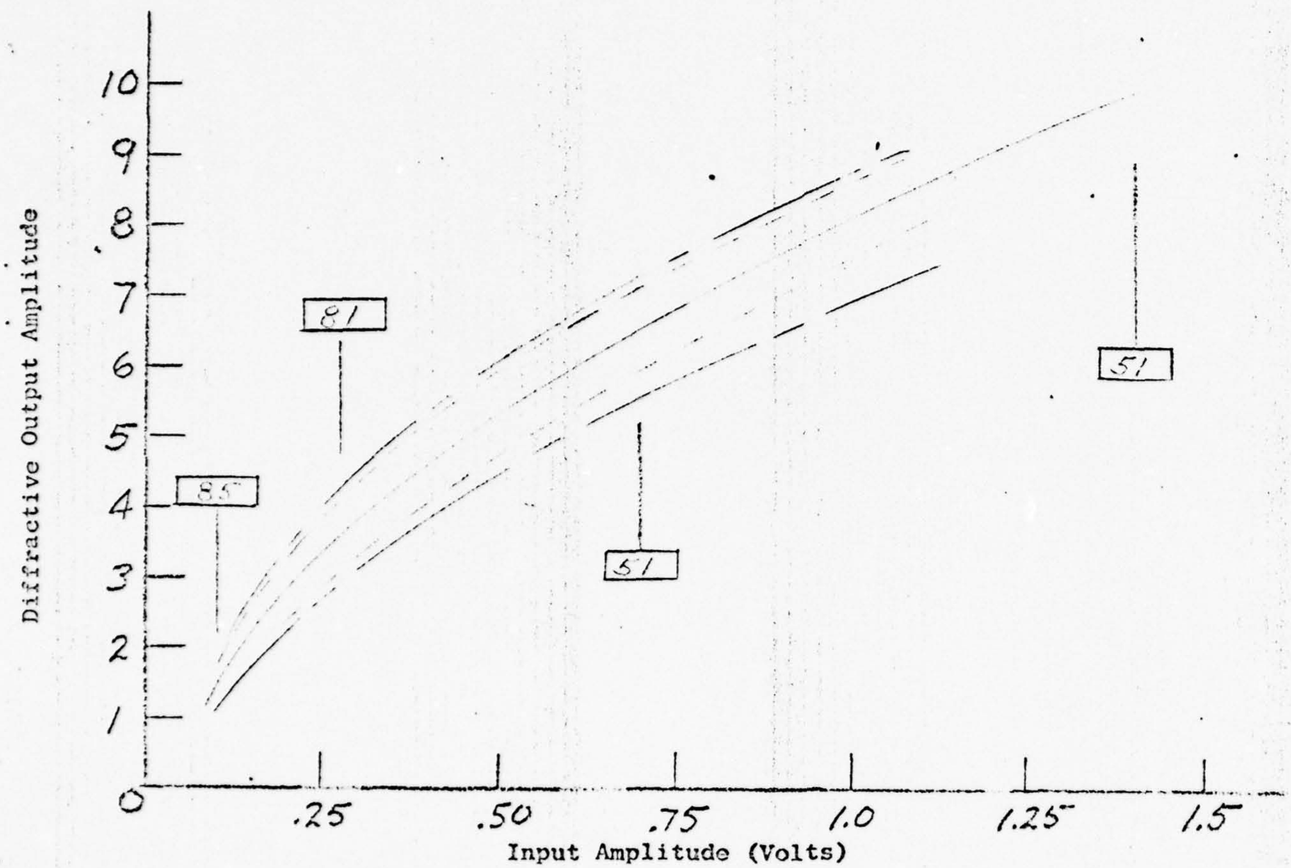

Figure 2. Diffractive Output Amplitude (Square Root of Intensity) Normalized to 10 vs Sinusoidal Input Amplitude RECORDAK DACOMATIC SO 266 FILM

Average of 6 Readings
Highest and Lowest
Average ± Standard Deviation
Standard Deviation of Biases (% Transmission of Maximum [1.4 v])

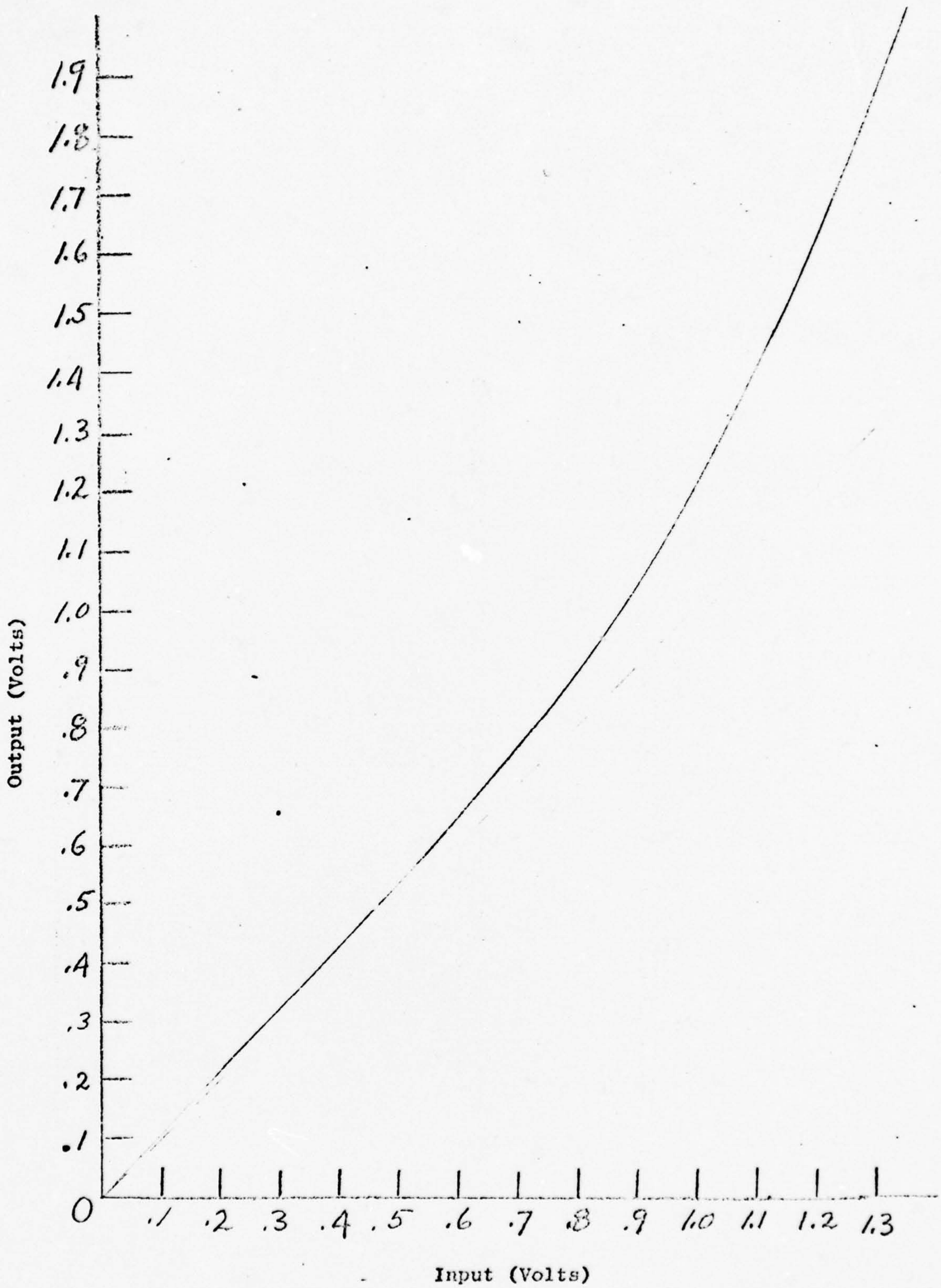

Figure 3. Estimated Non-Linear Amplification for Predistortion.

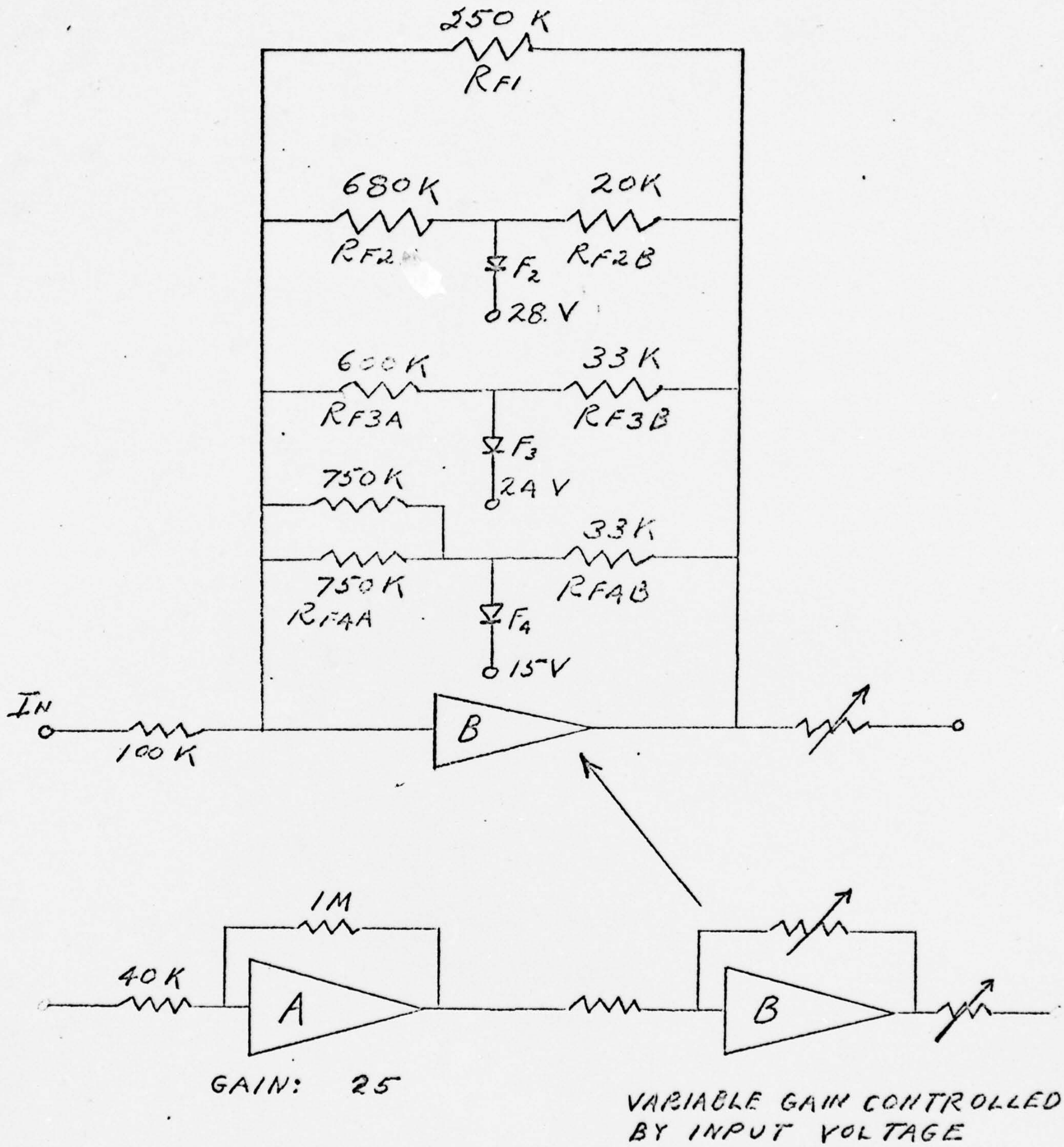

Figure 4. Predistortion Circuit

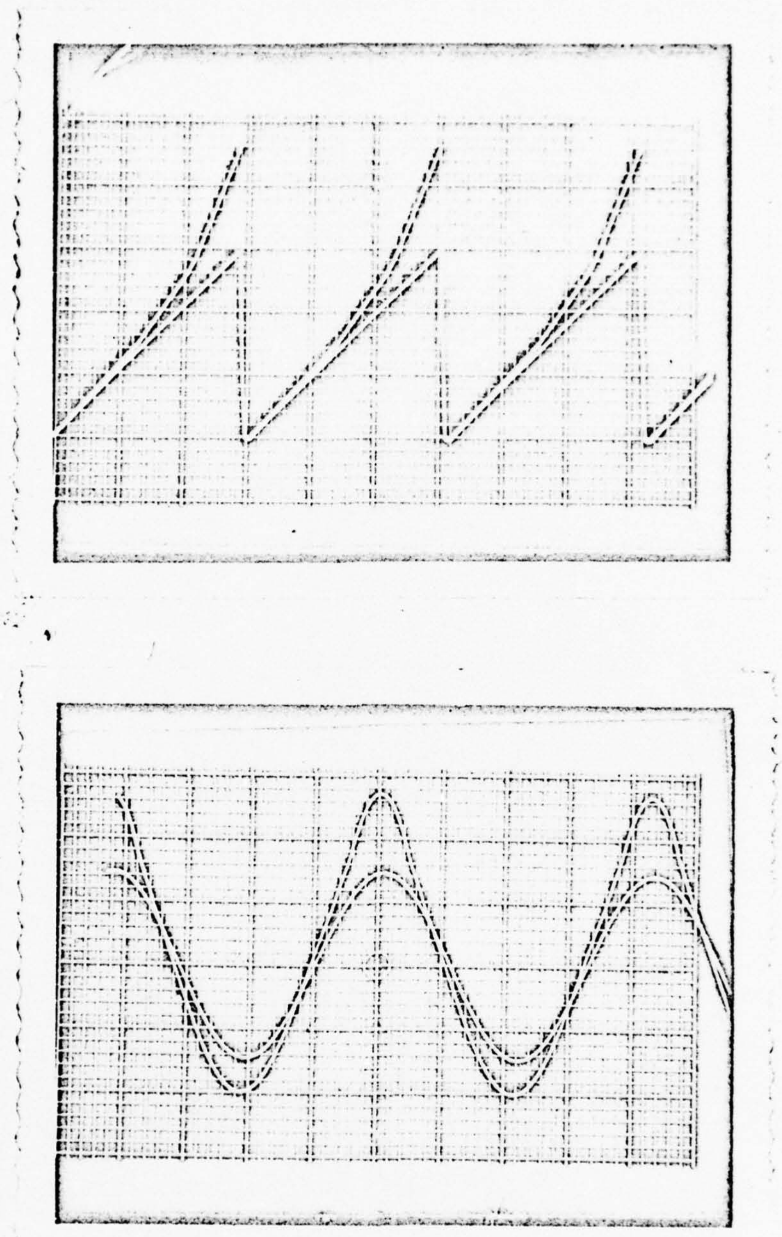

Figure 5. Oscilloscope traces of one-sided predistortion amplifier output. Above: Sawtooth input and output after predistortion. Below: Sine wave input and output after predistortion (with different scale factor).

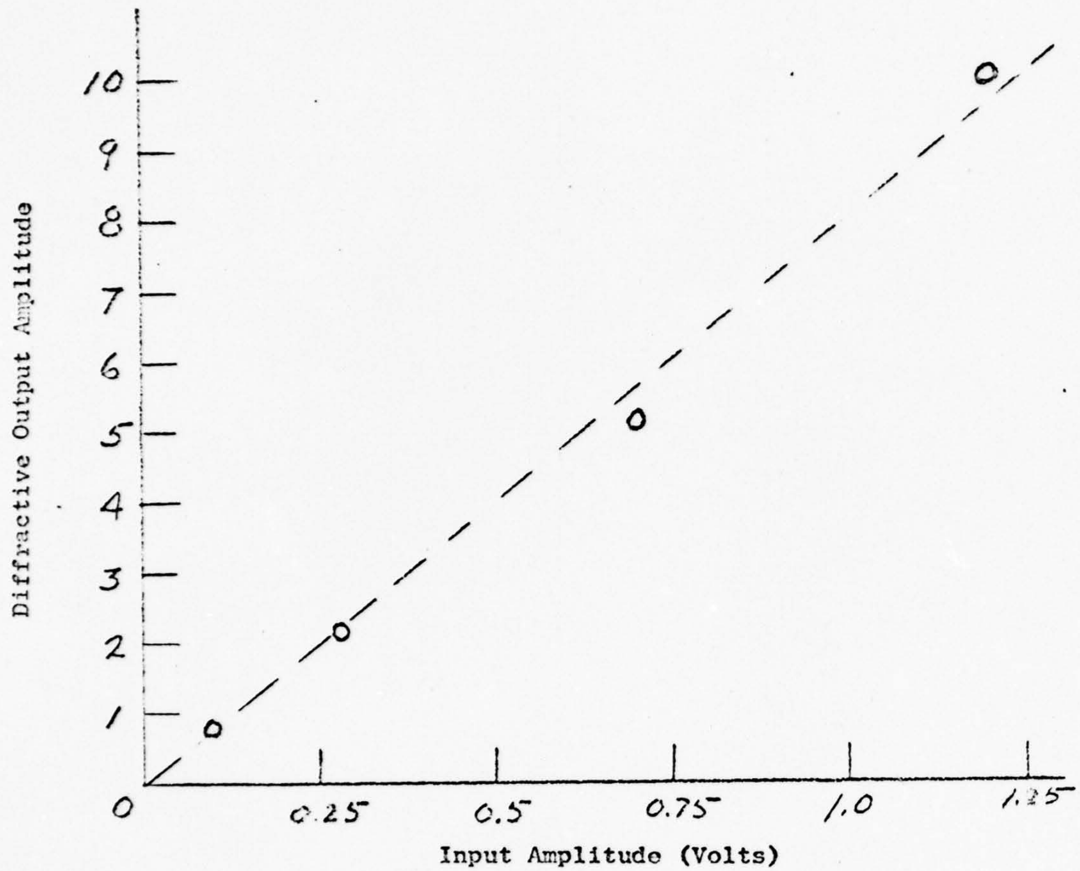

Figure 7. Two-Sided Predistortion. Diffractive output amplitude (Square-Root of Diffractive Intensity) normalized to 10 at 1.2 volts input vs sinusoidal input amplitude. Recordak Dacomatic SO 266 Film. Bias drift between channels approximately 18%. 5% harmonic distortion at 1.2 volt input).

APPENDIX 1

Description of film recorder presented to the Society of Exploration Geophysicists, November, 1964, at Los Angeles, California, by P. L. Jackson and R. H. McLaughlin.

(APPENDIX 1)

A VERSATILE PHOTOGRAPHIC SEISMIC RECORDER

by
Philip L. Jackson and Rowland H. McLaughlin

ABSTRACT

Variable-area, variable-density and amplitude seismograms can be produced when the spot on a cathode-ray tube face is used as a modulated light source. Channel selection and width are varied at will. The channels can be recorded simultaneously or successively with programmed time bases. A commercial oscilloscope is adapted to this purpose without invalidating it for normal use. The spot on the crt face sweeps along a slit in a mask. The intensity of this spot is modulated by voltage functions representing seismograms. By means of selective, sequencing circuitry combined with the sweep rate of the spot a seismogram channel is made to correspond to a particular segment of the slit. For simultaneous recording, time sequencing is used for commutation at a selection frequency far in excess of the highest seismic frequency. For successive recordings only a selected, solitary channel is gated, so that no spot is incident upon the remaining segments of the slit. The slit is imaged with a lens onto the transported film. The present model, constructed for variable-density, records up to 400 cycles per inch; at this resolution an entire conventional exploration seismogram can be recorded within two inches of film. Amplitude recordings are made by successively modulating the position of a constant intensity spot. Channel widths can be narrow enough to allow recording of 500 channels per inch. Film transport is designed for either 35 mm or 70 mm film. A drum type transport is used for accurate reregistering when recording seismograms successively. The time bases could be programmed by varying the frequency of the driving oscillator which powers the synchronous film drive motor. The recorder is built into a transportable unit.

Acknowledgement. This research was supported by the Advanced Research Projects Agency and was monitored by the Air Force Office of Scientific Research under Contract AF 49(638)-1078.

Draft SEG Paper

Section 1

At last year's meeting in New Orleans, we presented the basic techniques of seismic data processing by the use of highly coherent light from a mercury arc or helium-neon laser. The work we presented was the result of an investigation of optical processing at The University of Michigan under a VELA UNIFORM contract which started in June of 1961. Last year we did not have a satisfactory camera to record seismograms at spatial frequencies needed for the proper use of optical diffraction. Since that time we have designed and constructed a seismic recorder especially for

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optical processing.

1 Although primarily designed for variable-density, the recorder turned out to be versatile; it can also record wiggly-line, digital code, and could be made to record variable-area. Several other features, such as variation of channel widths, selection of channels, and the choice of simultaneous or sequential recording give added versatility.

2 The recorder consists of a cathode ray oscilloscope, imaging lenses, film transport, and electrical circuits for commutation, amplification, and film drive control.

Modulated light from the cathode ray tube is imaged through a slit upon slowly moving film. The slit reduces the light spot size and thus increases the frequency response of data recorded on the film. Segments across the face of the cathode ray tube are made to correspond to data channels by means of solid-state commutation. A drum type transport is used for accurate repositioning of the film.

3 We have altered a commercial oscilloscope so that a scanning spot can be modulated in brightness. The alterations are minor. They can be quickly switched out when it is desired to use the oscilloscope for other measurement purposes. A light-tight tube, which also serves as a lens positioner, connects the oscilloscope to the continuous strip camera. The camera box is removable. It is positioned on Teflon runners located on top of the case containing the commutator and the film drive control.

4 At present we are recording nine channels of variable-density earthquake seismograms and a sawtooth reference function. The recorded length of this film is 1-3/4 inches. Total harmonic distortion of the variable-density was found to be 15%.

5 Here is the frequency response curve for variable-density film recorded with this instrument. The 5/1000ths of an inch slit width limits the higher frequency responses. Both the lenses and the film have much higher frequency responses than shown here. For optical processing the interference of light rays is used, so this curve is in terms of light amplitude rather than the more commonly used light intensity which would be the square of this curve.

6 Digital code can be recorded by making the film either opaque or transparent. The highest bit rate on this illustrative recording is approximately 400 bits per inch. If the slit width were sufficiently reduced the present system would be limited by the lens resolution to about 2500 bits per inch. 2500 bits per inch corresponds to an undemanding 50 lines per millimeter lens resolution. We think at least a hundred and probably several hundred channels could be recorded on 35 millimeter film under a criterion that no ambiguity exists between opaque and transparent bits when the film is projected.

7 To obtain a wiggly-line seismogram the position of a spot along the slit is made to respond to the amplitude of the data input.

I should like to point out that our illustrations are initial results. For instance, the cathode ray tube is a standard P11 phosphor tube. Special magnetic deflection tubes are available with which a light spot size can be produced which is one-fifteenth the diameter of the present spot. Also, we have made no attempt to use a smaller slit for finer resolution.

We now will show each part of the recording system in greater detail.

8 With the camera box open we see a drum, Mylar belt drives, and a synchronous motor. During operation the motor and belt drive rotate continuously. The drum is actuated through a felt-faced clutch which is spring-loaded against a revolving disc. A latch holds the drum stationary in the starting position. The drum is rotated by releasing this latch. This mechanism enables us to position the film accurately for sequential recording.

9 A pre-assembly plan view shows the film drive in more detail. A synchronous motor and three stages of belt drives give a nominal film speed of 5 inches per minute. Positioning rings can be placed on the drum in these two slots so that 35mm film can be used as well as 70 mm. The film is wrapped around the drum so that the two ends are placed between the small rubber pinch rollers, and it is tightened by turning the knurled knob.

10 Here are the measurements of the smoothness of various drive designs. As you undoubtedly know, if small drive belts break in the field, a selvedge-edged brassiere strap, sewn together at an angle, is usually equal or

superior to many commercially furnished belts. However, we have found, after long investigation, that Mylar belts have given the smoothest drive of many possible mechanisms.

11 The modulated light source sweeps, and the sampled data appears, along this slit, which is mounted against the glass face of the cathode ray tube. The slit is adjustable in width.

I have presented the general features of this instrument to give an idea of its capabilities and of its present performance. However, electronic problems were of great interest on this project; Mr. McLaughlin will now present the means by which he solved these problems.

A VERSATILE PHOTOGRAPHIC SEISMIC RECORDER

Part 2

Introduction

We have seen earlier that the recorder contains three principal parts:

a film drive unit

a modified cathode ray oscilloscope and

a commutation and control unit.

The latter two parts, which comprise the electronics of the recorder, will now be treated in greater detail.

Scope Modification

A standard commercially available Tektronix model 531A Cathode Ray Oscilloscope was used as the basic source of modulated light for the camera. Three minor modifications were made to the scope to make it suitable for this purpose. The first modification labled "1" in the figure consisted of replacing the normal P1 cathode ray tube, with a photographic blue P11 tube. The second modification was necessary so that the incoming data signals would vary the brightness of the light produced by the cathode ray tube. The vertical amplifier of the scope is used to amplify the data signals in the

normal way, but the signals are then applied to the grid of the cathode ray tube. The signals thus applied cause the beam current of the cathode ray tube, and hence, the brightness of the light to vary in accordance with the amplitude of the signal. This change was implemented by the circuits labled "2" in the block diagram. The amplified data signal was obtained from the signal pick-off point in the vertical amplifier normally used to synchronize the sweep internally. The amplified signals are then applied to the grid of the cathode ray tube through a mixer which was built and added to the oscilloscope. This new circuit not only passes the seismic data to the grid of the cathode ray tube in the manner desired, but also retains the sweep retrace blanking function which is necessary to extinguish the cathode ray tube trace during sweep retrace and sweep quiescent periods. The entire data channel is D.C. coupled so that even very low frequency signals will be passed. The new circuit just described was constructed using transistors mounted on a small circuit board that fits readily into available space inside the oscilloscope.

The third modification labled "3" in the figure replaces the vertical position control in the vertical amplifier which is, of course, no longer effective. Control of vertical position is required to center the cathode ray tube trace in the slit.

The oscilloscope may be reconverted for normal test use by operating switches S_1 and S_2.

Data Amplifier and Commutator

We have heard previously that this recorder has the capability of recording several sources of data simultaneously by making use of a sequentially sampling commutator. This scheme is shown schematically here, wherein the commutator is represented as a multiple position switch which selects among the data inputs and presents the selected input to the oscilloscope. Although the commutator works in the manner of a stepping switch, or a mechanical whirling disc and brush mechanism, this commutator is a solid state device with no moving parts. It operates at a basic sampling rate of 1000 cycles per second, which means that 100 channels are successively sampled in a total period of one millisecond. The commutator may also be operated at a 10,000-cycle sampling

rate for successively repeating 10 channels of data. In this case, ten channels are sampled every 0.1 millisecond. The solid state switching circuits switch from one channel to the next in less than a tenth of a micro-second so that the commutator could be operated at much faster speeds if desired. This circuitry is contained in a standard printed circuit card rack as shown in this photograph. The commutator was designed and built at the University of Michigan, but the sequence which controls the commutator is constructed from commercially available logic cards. The commutator consists simply of a switched amplifier (one for each data channel to be recorded) and a mixer to which each of these amplifiers is fed. The switched amplifiers are controlled by a pulse in such a way that a signal is passed only when a control pulse is present. Thus, in order for this circuit to act as a commutator it is merely necessary to provide a succession of pulses, first, to switched amplifier one, second to switched amplifier two, and so on in turn to each switched amplifier of the group. Manual switches S, S_2, through S_{10} prevent the control pulse from reaching the switched amplifier at all, and hence any channels desired

may be left inactive. The switched amplifiers have a frequency response which is flat from DC to four megacycles, well in excess of the response needed for this application.

The next figure shows the manner in which the controlling pulses are generated. The circuit starts in the upper left with a 100 kilocycle crystal oscillator. The crystal oscillator was chosen to give the necessary time base stability for sequential repetitive recording of groups of channels during separate rotations of the film drum. The oscillator is followed by a decade counter which is a circuit consisting of four sequential flip flops connected in a divide by ten arrangement. The output of the counter is therefore a ten kilocycle signal. A decimal decoding matrix is connected to the decade counter. This circuit recognizes the ten discrete states present in the decade counter and produces, upon ten separate lines, a pulse which is present only once during the scale of ten. In other words, if we call these ten intervals, T1, T2 and on through T-10, the pulse will appear on line T-1, then on T-2, and so on until the pulse has appeared on T-10. This may be seen from the waveforms labled 100 Kc, T, T2, and T10. This sequence

will repeat continuously at a ten kilocycle rate. The shaded portion shows the second reoccurrence of the signals. These pulses when applied to the switched amplifiers become the control pulses which activate the data amplifiers one after another until all 10 have been presented in turn to the cathode ray oscilloscope.

It should be noted also at this point that pulse T-1 is present until very shortly before pulse T-2 appears, and that the switching time between the disappearance of pulse T-1 and the appearance of pulse T-2 is the order of 1/10th of a micro-second. This means that in the first place, when these pulses are applied to the data switched amplifiers, only one channel is present at any given instant, and in the second place, the switch from one channel to the next is practically instantaneous. So far we have seen how a sequence of ten pulses is generated and how this sequence in turn controls ten data channels so that they are applied one after another to intensity modulate the cathode ray oscilloscope.

Here we see how by a logical extension of this technique, 100 data channels may be switched. A second decade counter and decoding matrix follows the first. This decimal converter

also produces a sequence of ten pulses each on a separate wire. Each of these ten pulses, however, are as long as the entire string of ten pulses coming from the first converter. Thus by selecting the pulses from the first converter, which are present during only the first pulse of the second converter, we have generated the first ten channels of a 100 channel sequence. This is shown by the channel 1 through 10 line in the left figure. This technique is continued until the entire group of 100 channels has been generated.

The group of 100 channels thus repeats at a one kilocycle rate, and the output at one kilocycle from the second decade counter is used to trigger the sweep of the oscilloscope so that one sweep occurs for every 100 channel control pulses. Two methods are used to select which of the 100 possible channels will be active at any given point in time. The first method is to control whether an individual channel will be present or absent on the display by interrupting the switching pulse if it is desired to remove that channel from the display. In this manner as the sequence of pulses is applied to the data amplifiers, a particular data amplifier is skipped by preventing its control pulse from occurring.

The second method of channel selection is by means of the manual group selector switch shown in the right hand figure. This switch selects whether channels one through ten, eleven through twenty, or some other group of ten channels will be present. An eleventh position permits all 100 channels to be present simultaneously. The output of the data commutator as it would be viewed on a test scope is shown here. This is a group of ten channels numbered from left to right. Channel one is off, channel two and three are present, while channel four is off, channel five is present and is being modulated by an input signal; six is present, seven and eight have been switched off, nine is present and ten is off. The pedestals corresponding to the active channels, brighten the cathode ray tube trace to form a light bias for the modulation.

The sampled levels of the modulation envelope may be clearly seen on channel 5. Notice that the pedestal amplitude swings equally above and below the light bias level, and that many discrete levels representing the various amplitudes during many commutated samples are evident.

The next picture shows this same group of channels as seen in the recorder. Notice that the channels fall between

the reticle lines as in the picture on the right and that channel 5 which is modulated appears brighter. The reticle lines were added to make identification easier in this picture. The length of the sweep is 10 microseconds per channel in both of these pictures. In this next picture we see the same group of channels, but representing in this case channels 51 through 60 of a one-hundred channel display. The sweep length has been increased so that each vertical reticle line measures 100 microseconds which is the display time required for ten channels. The entire base line in this picture is therefore 1 millisecond which is the display time required for 100 channels.

Here again is the overall view of the camera with now the input panel identified. The input jacks for the ten data channels, and the individual channel activation switches may be seen. The rotary switch on the far right is the group selector switch which selects which portion of a 100 channel display will be occupied by the ten data channels available.

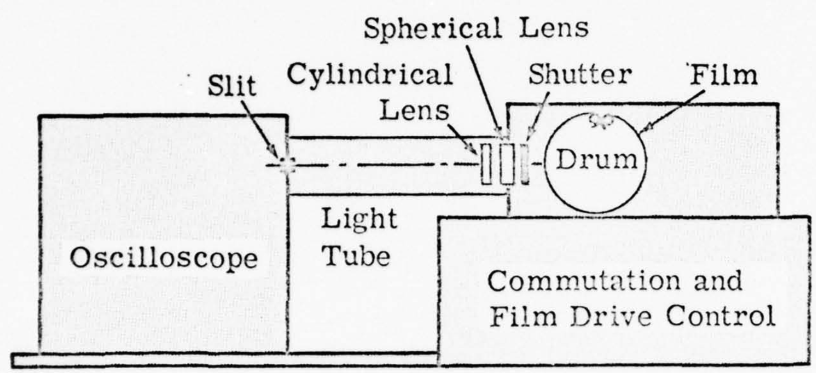
We have seen examples of data recorded on this camera using variable density, wiggly line, and digital techniques. No examples of variable area were shown since additional circuitry

is required to implement this technique. The circuits have not been built because no need for this capability presently exists at the University of Michigan. All that is required, however, is to cause the pedestal width of any channel to be modulated instead of the pedestal amplitude.

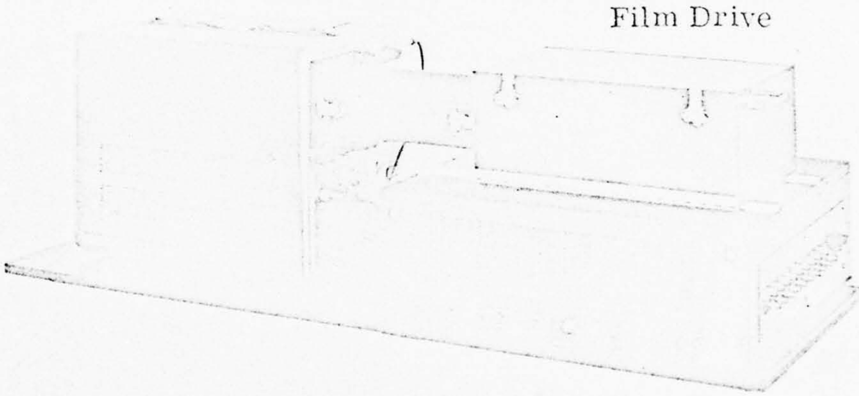
- Variable-Density
- Wiggly Line
- Digital Code
- Variable Area Capability
- Sequential or Simultaneous
- Control of:
  - Channel Widths, Selection, and Number
  - Film Speed (Continuous)

SLIDE 1

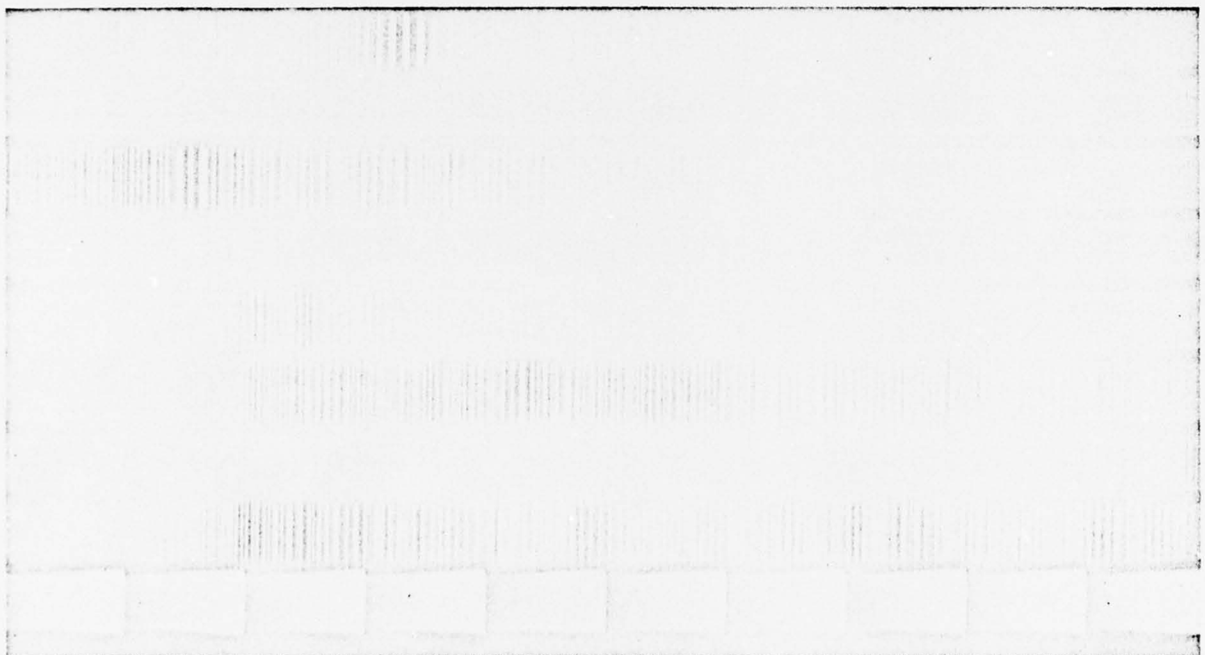
RECORDING LAYOUT



SLIDE 2



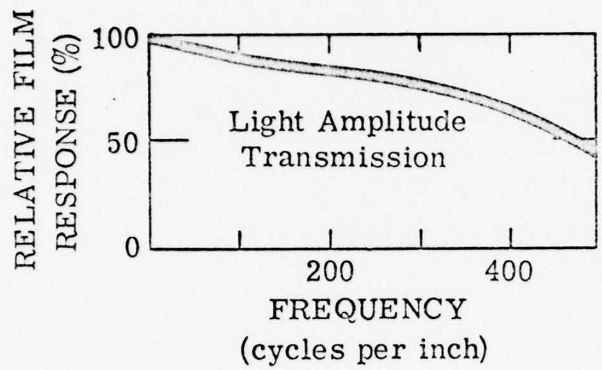
SLIDE 3



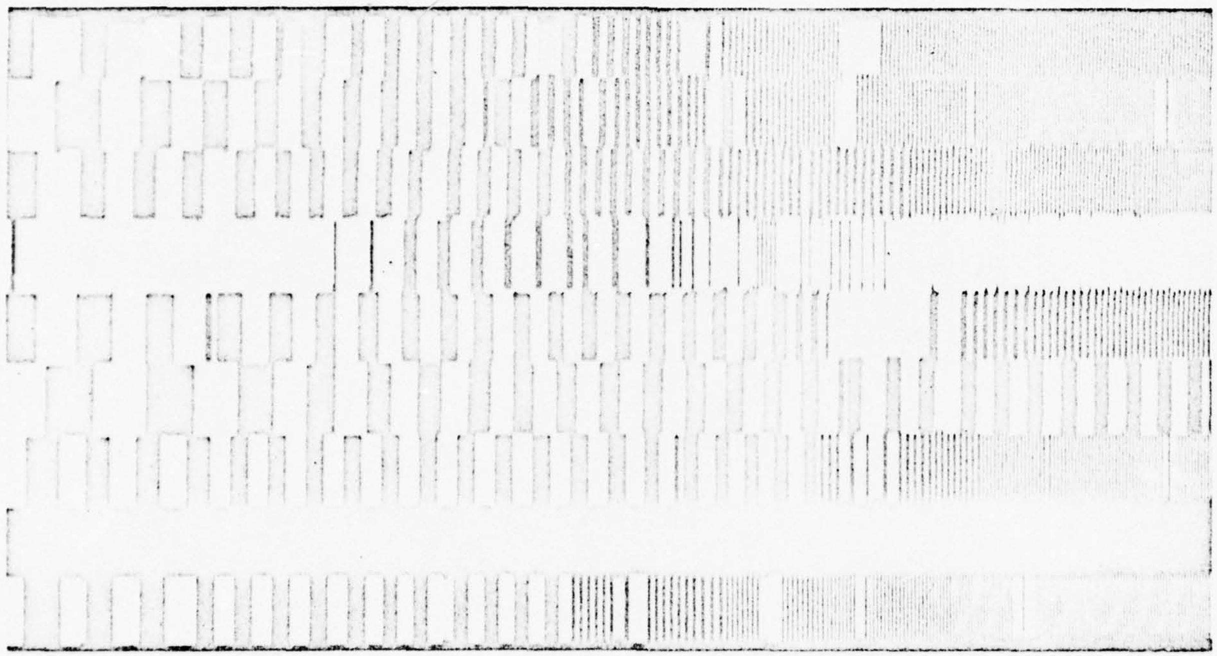
SLIDE 4

FREQUENCY RESPONSE OF RECORDER

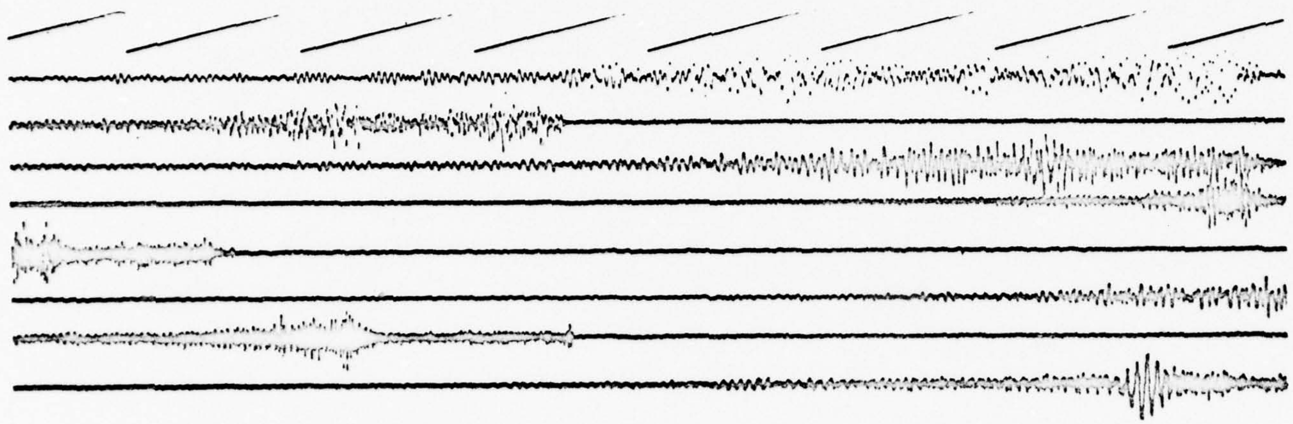
(0.005 Inch Slit)



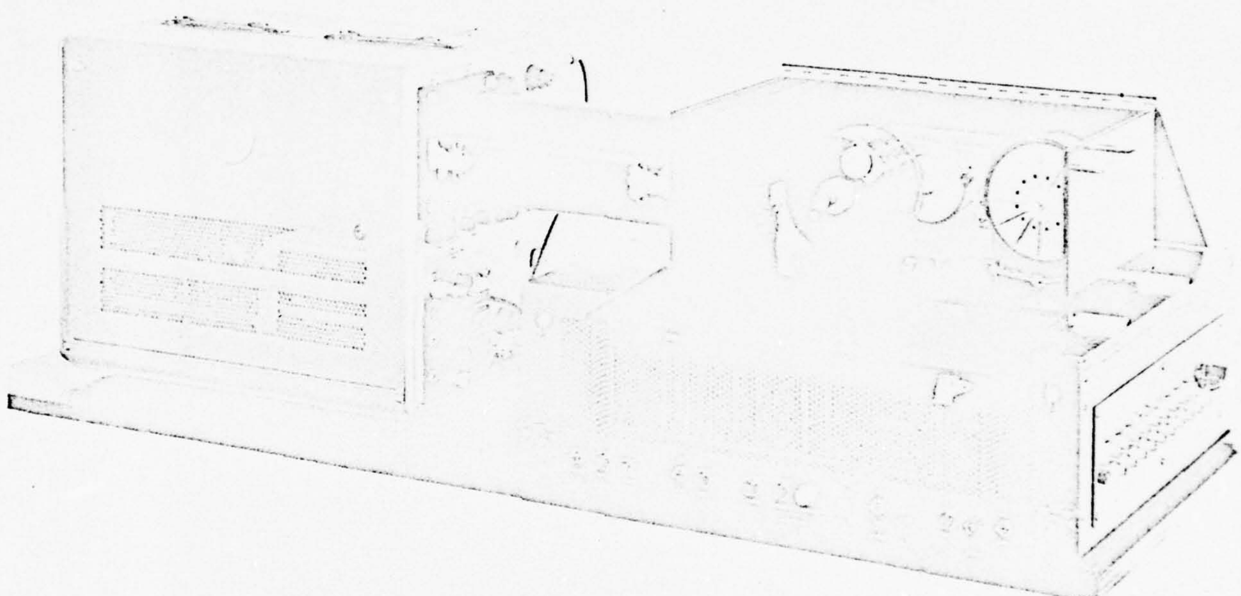
SLIDE 5



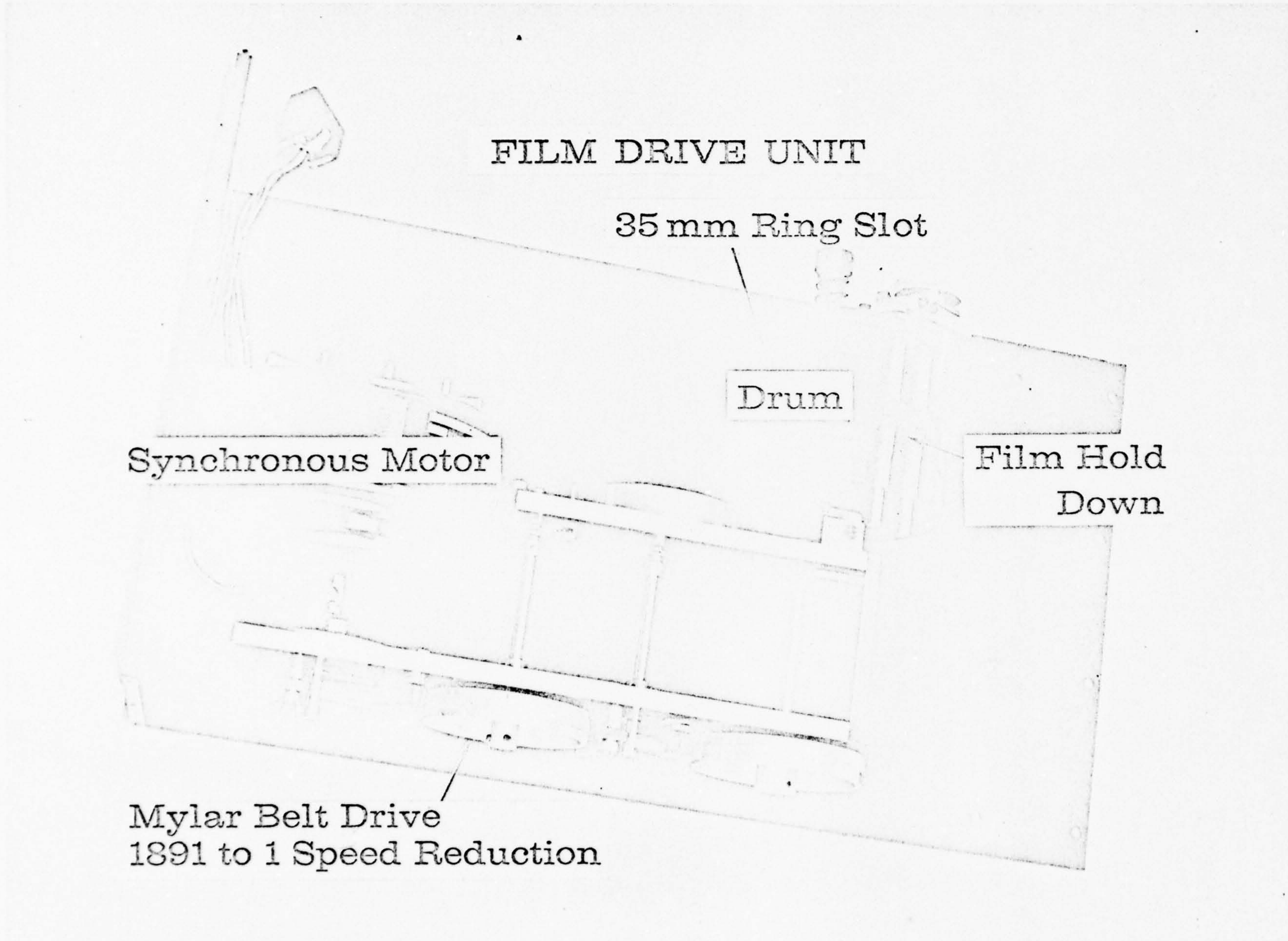
SLIDE 6



SLIDE 7



SLIDE 8

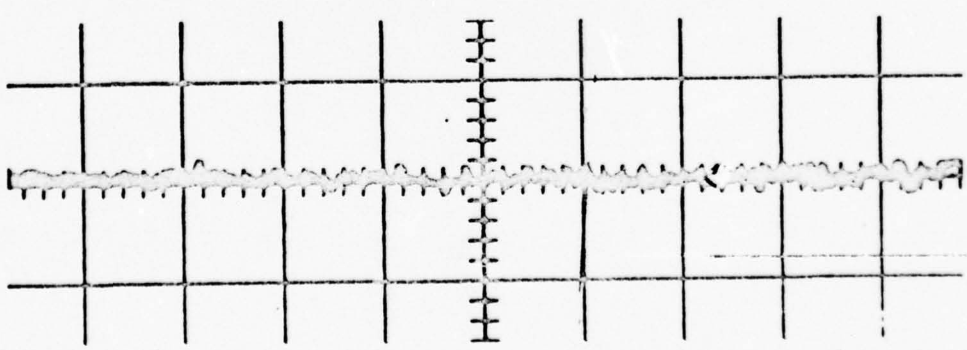

FILM DRIVE UNIT
35 mm Ring Slot
Drum
Synchronous Motor
Film Hold Down
Mylar Belt Drive
1891 to 1 Speed Reduction

SLIDE 9

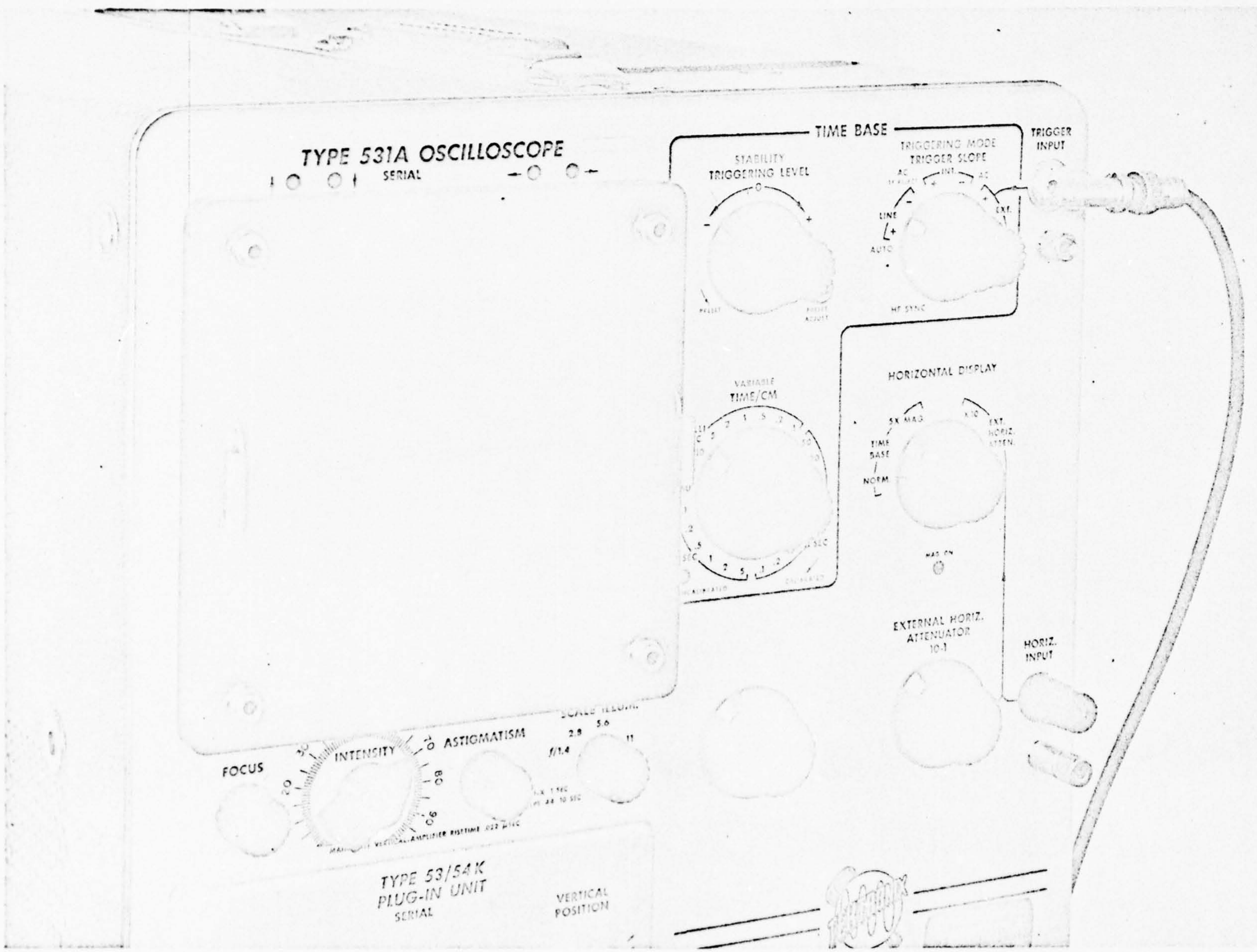
CAMERA DRIVE VELOCITY IRREGULARITIES

Gears

Nylon Brassiere Strap

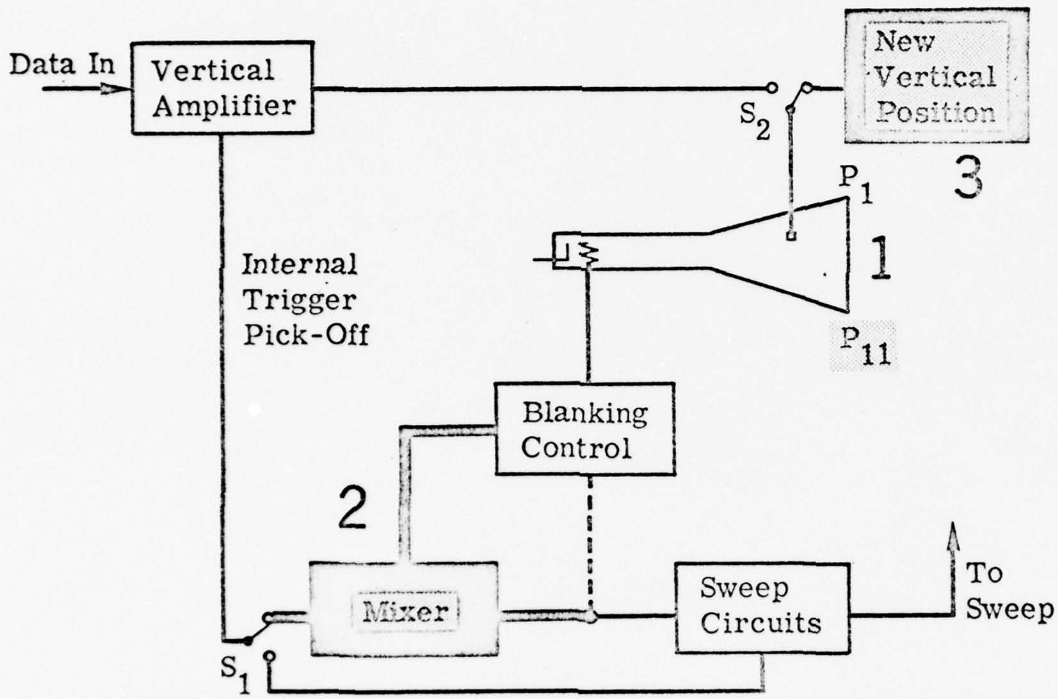


Mylar Annulus Belt



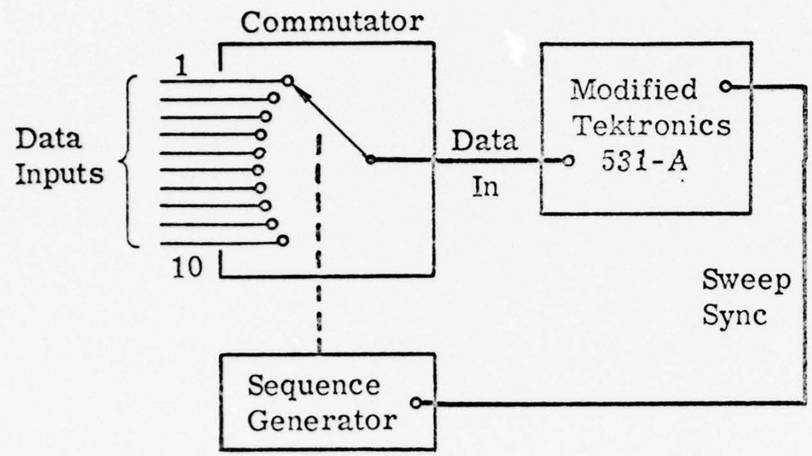
TYPE 531A OSCILLOSCOPE
SERIAL
TIME BASE
STABILITY
TRIGGERING LEVEL
TRIGGERING MODE
TRIGGER SLOPE
LINE
AUTO
EXT.
HF SYNC
TRIGGER INPUT
VARIABLE
TIME/CM
HORIZONTAL DISPLAY
5X MAG
TIME BASE
NORM
EXT. HORIZ. ATTEN.
MAG ON
EXTERNAL HORIZ. ATTENUATOR 10-1
HORIZ. INPUT
FOCUS
INTENSITY
ASTIGMATISM
SCALE ILLUM.
f/1.4
2.8
5.6
11
TYPE 53/54K
PLUG-IN UNIT
SERIAL
VERTICAL POSITION

SLIDE 11

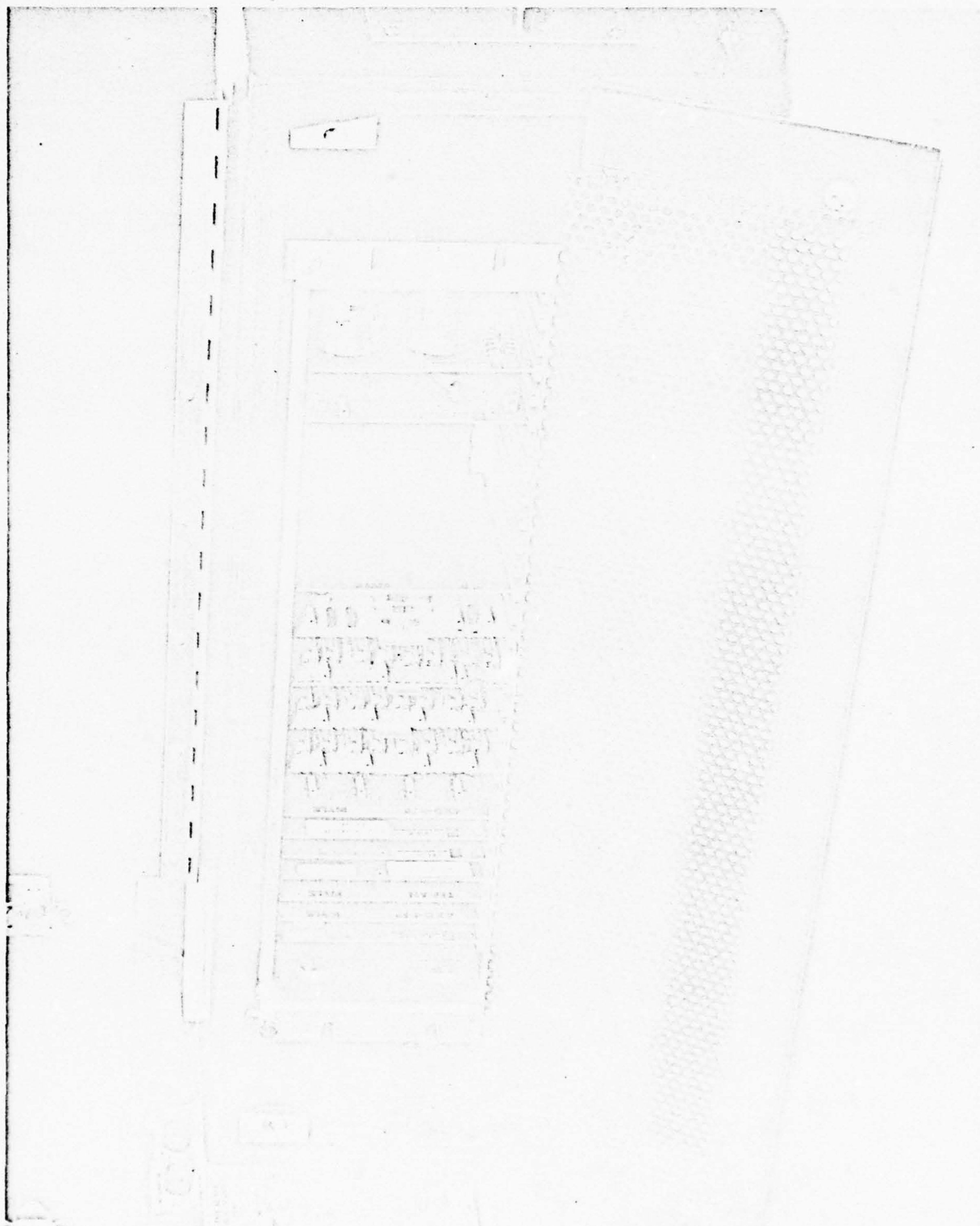


Data In
Vertical Amplifier
New Vertical Position
3
S_2
P_1
1
P_{11}
Internal Trigger Pick-Off
Blanking Control
2
Mixer
Sweep Circuits
To Sweep
S_1

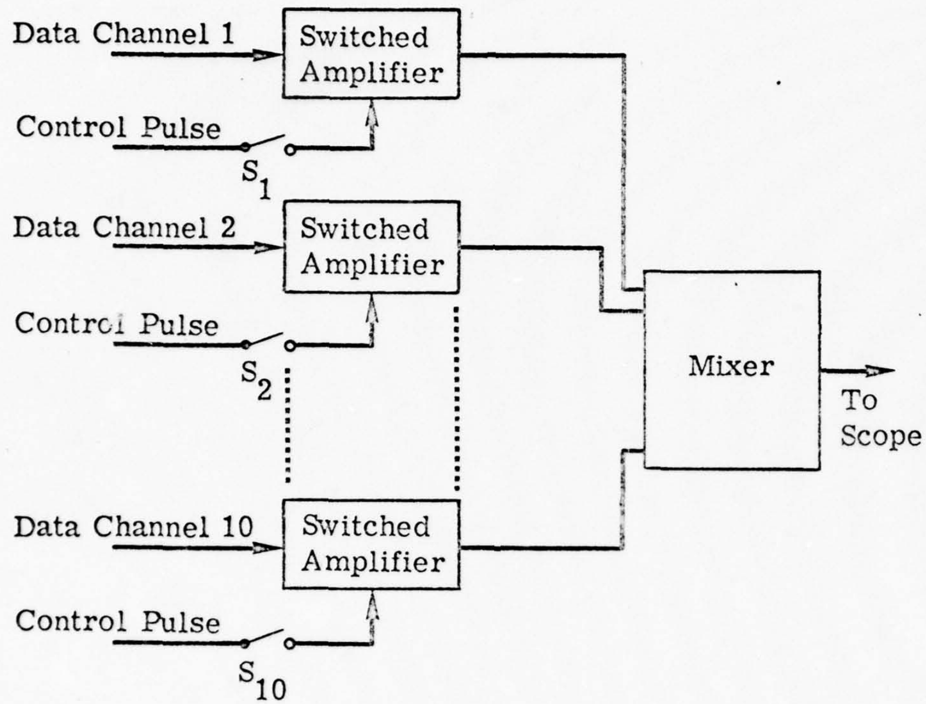
SLIDE 13


Commutator
1
10
Data
Inputs
Data
In
Modified
Tektronics
531-A
Sweep
Sync
Sequence
Generator

SLIDE 14

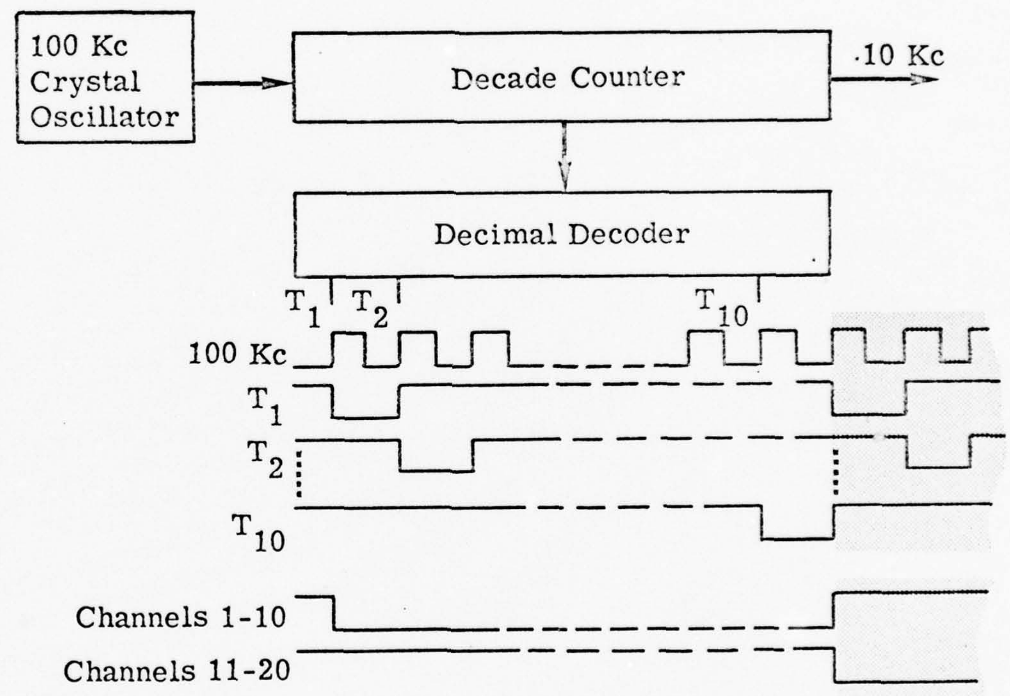


SLIDE 15

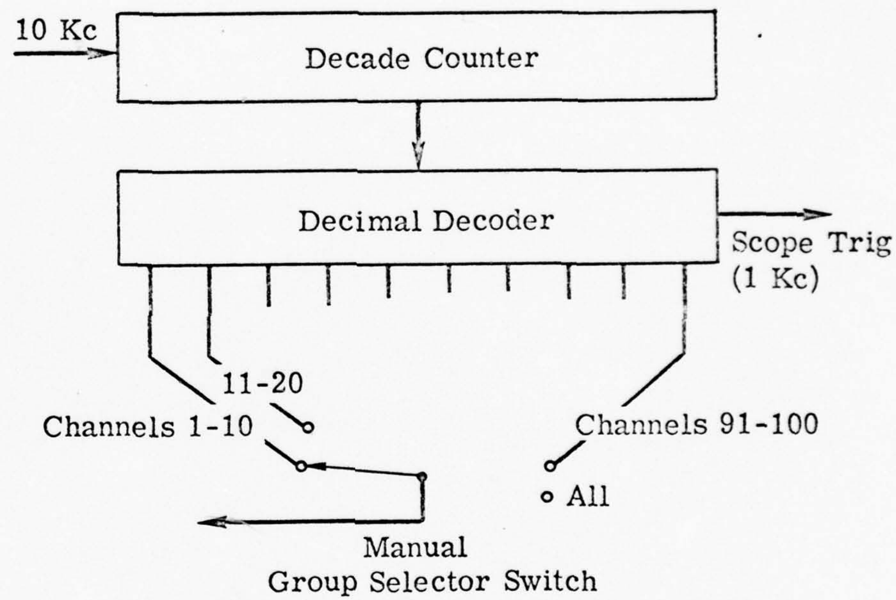


Data Channel 1
Switched Amplifier
Control Pulse
S_1
Data Channel 2
Switched Amplifier
Control Pulse
S_2
Data Channel 10
Switched Amplifier
Control Pulse
S_{10}
Mixer
To Scope

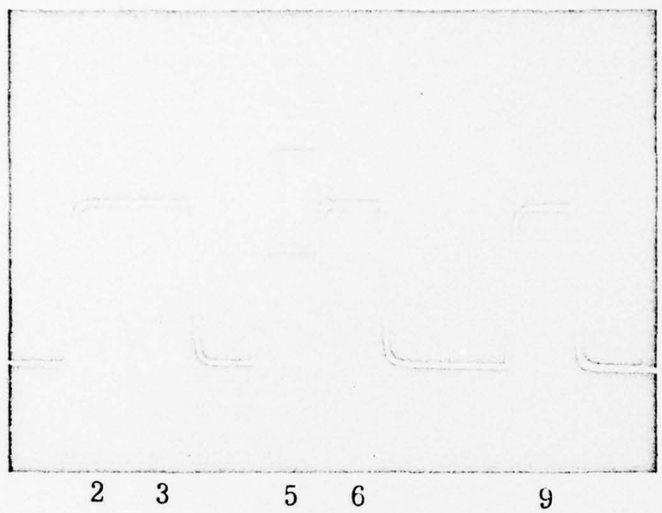
SLIDE 16


100 Kc Crystal Oscillator
Decade Counter
·10 Kc
Decimal Decoder
T1
T2
T10
100 Kc
T1
T2
T10
Channels 1-10
Channels 11-20

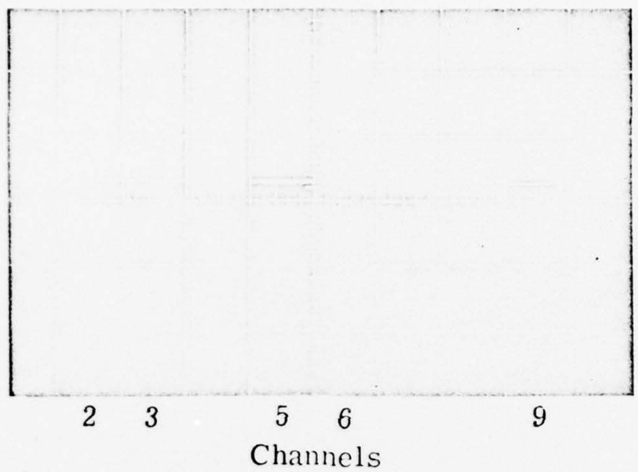
SLIDE 17


10 Kc
Decade Counter
Decimal Decoder
Scope Trig
(1 Kc)
11-20
Channels 1-10
Channels 91-100
All
Manual
Group Selector Switch

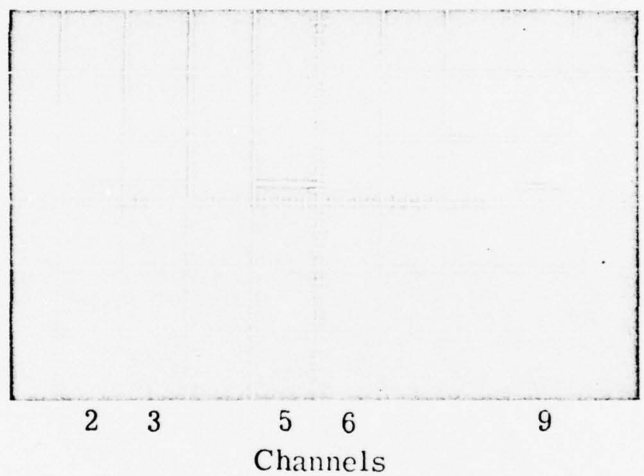
SLIDE 18



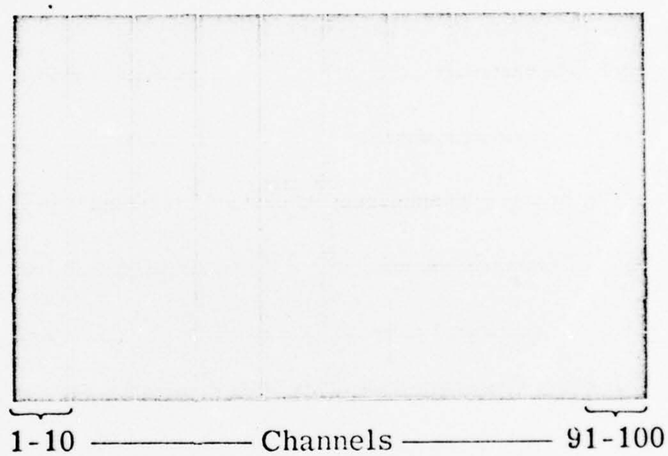
SLIDE 19



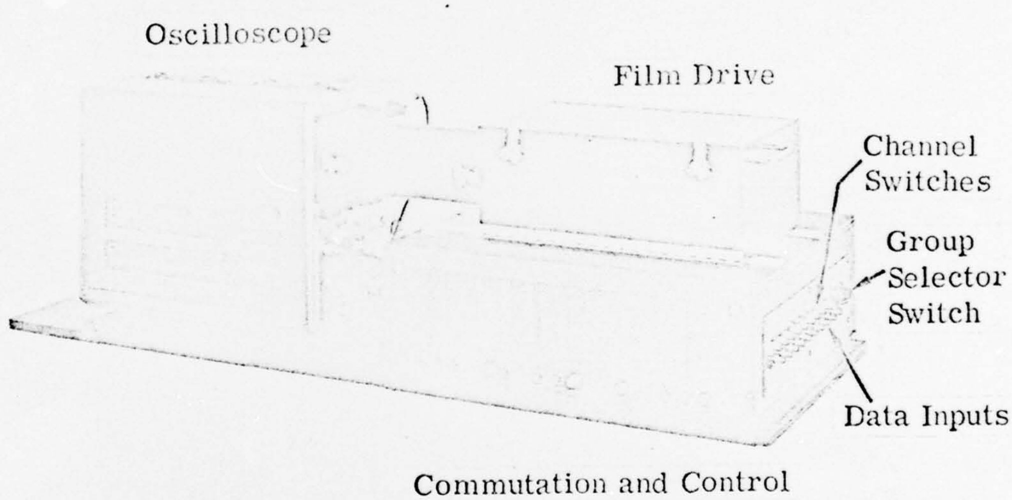
SLIDE 20



SLIDE 20



SLIDE 21


Oscilloscope
Film Drive
Channel Switches
Group Selector Switch
Data Inputs
Commutation and Control

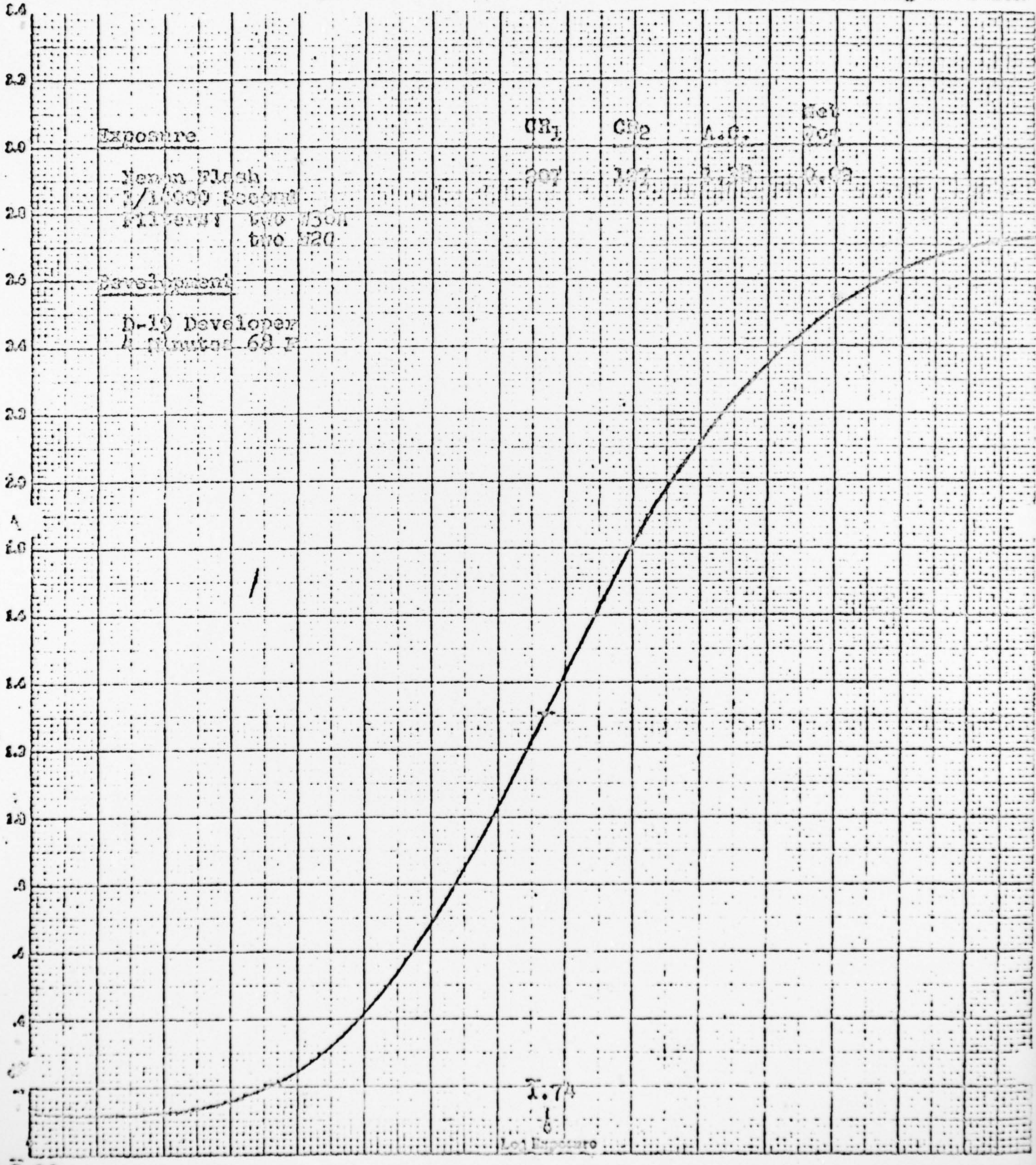
SLIDE 22

APPENDIX 2

Hurter-Driffield curve and modulation transfer function of Recordak Dacomatic SO 266 Film.

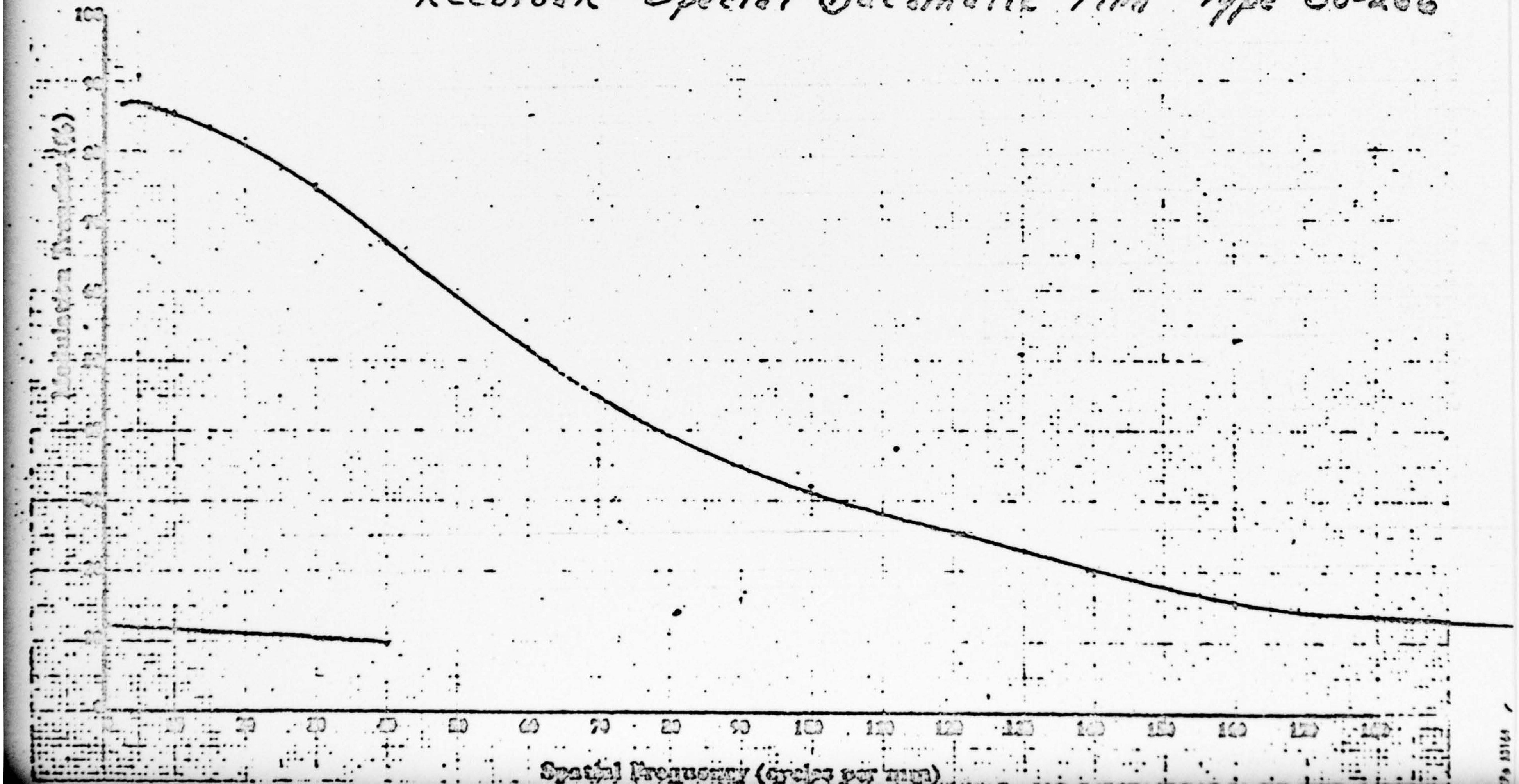
Recordak Special Dacomatic Film, Type SO-266

TR-17187
Film Testing Division



Date 5-27-63
Test No. MT-6305006
Emulsion SO-266
Development 5' D-19
Illumination Wr 98

Recordak Special Docomatic Film Type SO-266



APPENDIX 3

Appendix from Willow Run Laboratories internal memorandum 6400-M-2502, by J. W. Wescott with Appendix by P. L. Jackson.

Appendix

Correlation with non-coherent light, variously known as the Patterson, Robertson, Bragg, Meyer-Eppler, or "lensless correllograph" technique, conventionally uses two masks representing functions with different scale factors. The larger mask is illuminated with diffuse light, and the smaller mask is placed between the larger mask and a viewing screen at such a distance that a straight line drawn from any point (x,y) on the larger mask passes through the corresponding (scaled down) point on the smaller mask to a fixed point $(\sigma,\tau) = (0,0)$ on the screen where (σ,τ) are correlation variables. Thus the intensity (0,0) on the screen is the sum of the light transmission through one mask, f(x,y), multiplied by the light transmission through the second mask, g(x,y), which is represented by the integral

$$\phi\ (0,0) = \iint_A f\ (x,y)\ g\ (x,y)\ dx\ dy$$

For any point (σ,τ) on the output screen we find

$$\phi\ (\sigma,\tau) = \iint_A f(x,y)\ g(\ x+\sigma,\ y+\tau)\ dx\ dy$$

which is the non-normalized correlation function. The process is strictly based on geometrical optics; diffraction causes degradation, so the sizes of the masks are important.

A simple example is the autocorrelation of a square pulse, which is the equivalent of an aperture in one-dimensional optical representation. The autocorrelation function is a triangular wave, as shown in Figure 1.

The means of obtaining a correlation (or convolution) between a pair of two-dimensional patterns with non-coherent light apparent was first suggested for Patterson functions in crystallography. Robertson, Hagg, Bragg, and Vand (Buerger, 1962) showed different optical methods by which this correlation could be achieved. Meyer-Eppler (1946) appears to have first suggested the technique f non-crystallographic applications. McLachlin (1962) discussed this technique in terms of pattern recognition. Vanderlugt (1963) point out several limitations when describing what is essentially Bragg's configuration, in which lenses are employed as in the coherent light processor developed by the Radar and Optics Laboratory.

So far as I know, previous discussion about this technique has involved two masks, except for the use of several small lamps to represent "points". However, nothing in the theory of this technique precludes the use of an "image" in place of the first mas "Image" is used loosely here in the sense that a light pattern acts the same way as a mask. The image can be a crt display, image inte sifier, or direct camera image on ground glass. A crt display rece has been used with recognizable results with the geometry of a seis array as the object (Jackson, 1965). A crt presentation rather than a mask was used for investigation of the possibility of real-time correlation. The single requirement for the first mask is that the light emerging from the mask diverges uniformly from

each point over a large enough angle to encompass the smaller reference mask. Any type of image with diffuse light satisfies this condition.

A reference mask for a relatively small object in a large scene will act as a correlator for the correspondingly-sized object in the scene. But for the field itself the mask will function as a distorted pinhole in a camera obscura. Thus if the field is very bright the intensity value at the position of correlation will be greater than the intensity for a relatively dark scene. The correlation pattern "rides", so to speak, on the background value of the field. This may cause difficulty in visual estimation. However, with direct visual readout it should be considered that the human eye adjusts to light intensity levels within a range that is well over 100db, and discriminates intensity levels differing by less than 1%. It is possible to modulate the brightness of presentation as a function of average brightness level of the scene. Also, it is possible to use the negative of a scene (by reverse z-modulation on a crt, for instance) when the object, such as a military vehicle, is darker than its environment.

The method of "lensless correlography" may be derived as follows: With the geometry as in Fig. 2, a function f can be represented along line A by making the transmission at x equal to f(x). A function g can be represented along B by making the transmission at the point ξ on B equal to $g(\frac{a+b}{b}\xi)$. The dimensions of the transparency on B will be reduced by a factor $\frac{b}{a+b}$ from those of the transparency on A.

Note that the straight line from O on C to x_i on A intersects line B at the point $\frac{b}{a+b} x_i$, and at these two points the transmissions are $f(x_i)$ and $g(\frac{a+b}{b} \cdot \frac{b}{a+b} x_i) = g(x_i)$ respectively.

Now consider a wedge whose base is Δx_i with midpoint x_i on Line A, and whose apex is O on line C (refer to fig.2). The average value of f within the segment "Δx_i" is taken as $f(x_i)$. If, in an optical system the length "Δx_i" of a transparency along A is diffusely lighted, the light intensity at O on C under the limitation of straight-line propagation of geometrical optics will be, $I_o\ (\Delta x_i) \cong K\, f(x_i)\ g\ (x_i)\ \Delta x_i$.
where K is a constant depending on the incident light intensity on Δx_i and the distance a+b. The total intensity at the point O resulting from the superposition of the contributions of all the Δx_i will then be

$$I_o \cong K \sum_{i=1}^{n} f(x_i)\ g\ (x_i)\ \Delta x_i .$$

Taking limits as $\Delta x_i \rightarrow 0$, $n \rightarrow \infty$ this becomes

$$I_o = K \int_o^x f\ (x)\ g\ (x)\ dx$$

which is the correlation function ϕ_{fg} at 0; i.e., $\phi_{fg}(0) = I_o$.
Now consider any point τ on line C. The wedge in dashed lines in Fig.2 is shown as if the solid wedge were rotated about the point $\frac{b}{a+b} x_i$ on line B, so that the new apex is at τ on the correlation line C, and the base of the wedge is centered at $x - \frac{a}{b} \tau$ on line A. Thus the intensity at τ is given by

$$I_\tau = K\ f\ (x_i - \frac{a}{b} \tau)\ g\ (x_i)\ \Delta x_i .$$

If we make an extension to all Δx_i,

$$I_\tau = K \sum_{i=1}^{n} f\ (x_i - \frac{a}{b} \tau)\ g\ (x_i)\ \Delta x_i .$$

We now let max $|\Delta x_i| \to 0$ and $n \to \infty$, so that I_τ goes over into the integral $I_\tau = \phi_{fg}\left(-\frac{a}{b}\tau\right) = K\int_0^x f\left(x - \frac{a}{b}\tau\right) g(x)\, dx$. Thus the correlation function is obtained with this optical system. The extension from two lines to two planes naturally follows. The one-dimensional case is actually a special case of the multi-dimensional case, and was treated in one-dimension for simplicity. The geometry for two dimensions is shown in Figure 3.

A pattern which has two-fold rotational symmetry is always obtained with two-dimensional autocorrelation, so, in addition to the intensity at the center of a correlation function, the correlation pattern has a distinct and identifiable pattern for recognition.

References

Buerger, N. J., Vector Space, Wiley, 1962.

Jackson, P. L., Report 05178-56-L, IST, University of Michigan, 29 November, 1965.

McLachlan, D., "The Role of Optics in Applying Correlation Functions to Pattern Recognition", JOSA, 52, 4, 1962.

Meyer-Eppler, W., "Die Funktionalanalytische Behandlung des Schattenproblems", Optik, 1, 1, 1946.

Vanderlugt, A., Signal Detection by Complex Filtering, IST, U of M Report 2900-394-T, July, 1963.

JWW/mm

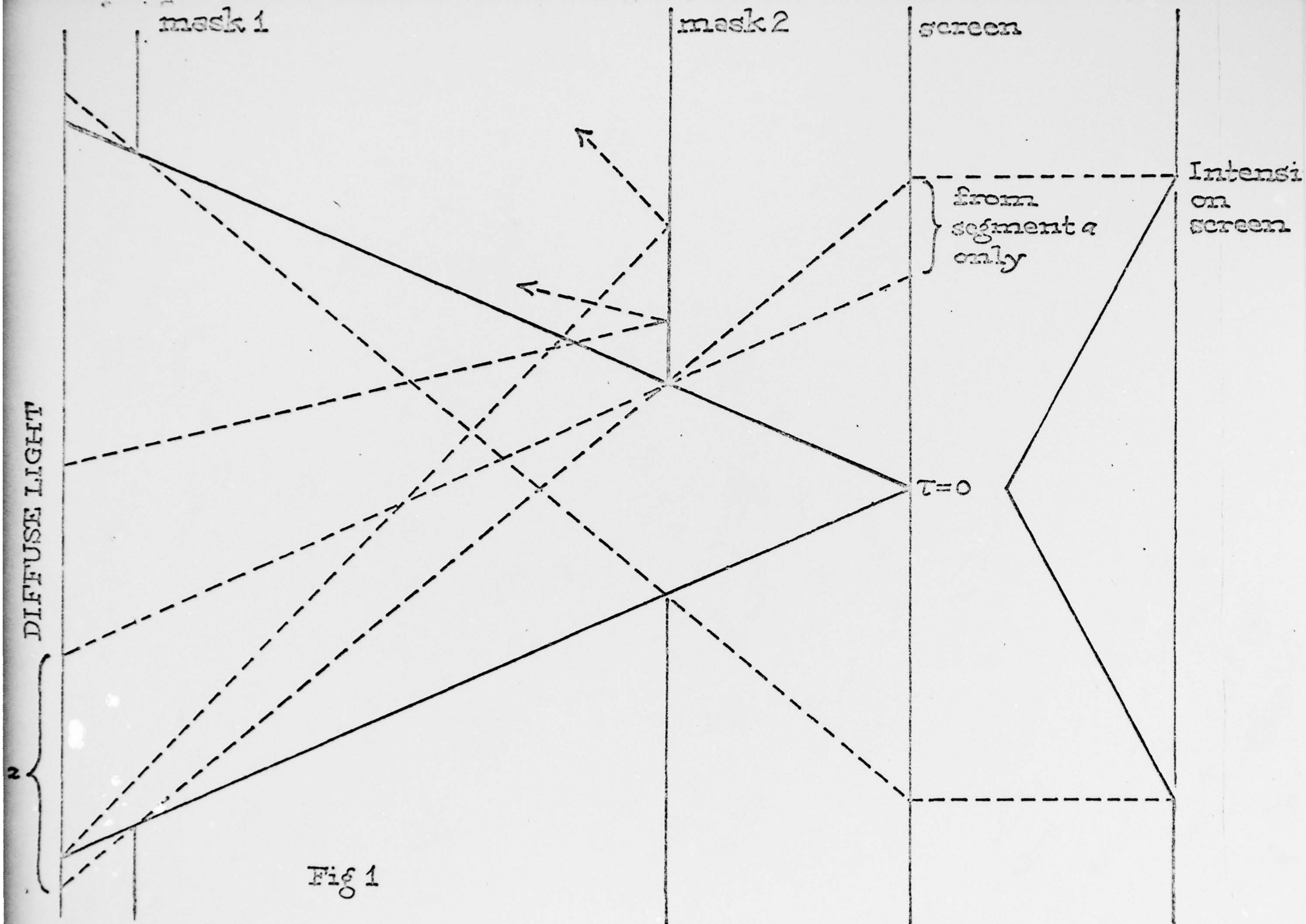

mask 1
mask 2
screen
Intensi
on
screen
from
segment a
only
$\tau=0$
DIFFUSE LIGHT
2

Fig 1

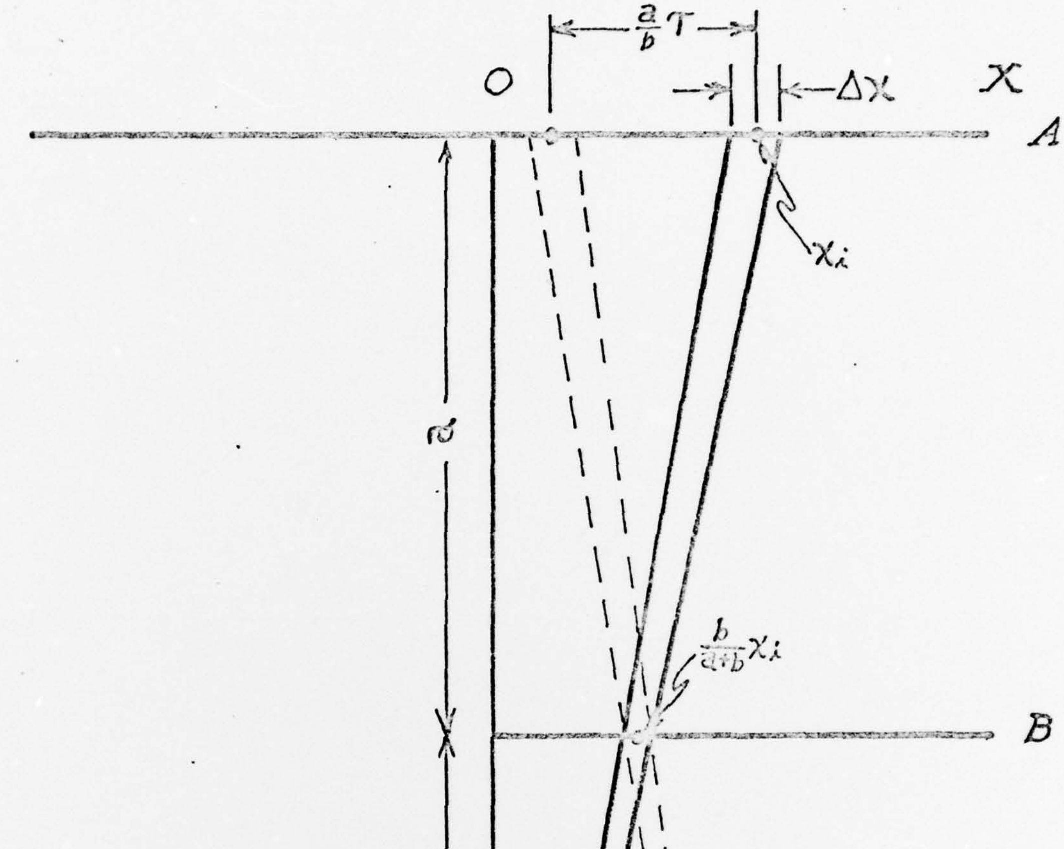


Fig. 2

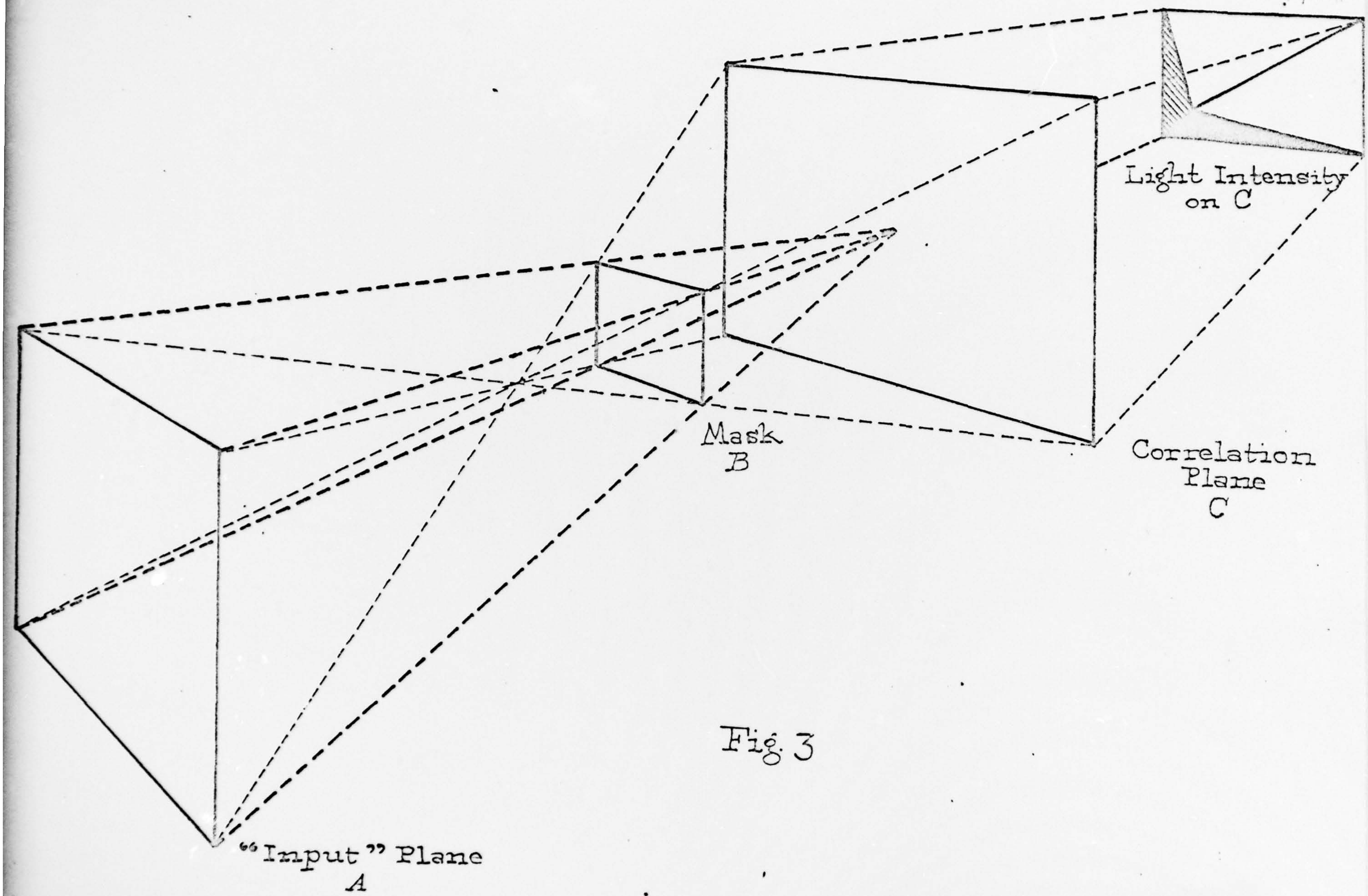

Light Intensity
on C
Mask
B
Correlation
Plane
C
"Input" Plane
A

Fig. 3